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THE GEOLOGY OF THE LEWISIAN COMPLEX
NEAR POOLEWE, ROSS-SHIRE

by

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SUMMARY

The Lewisian rocks near Poolewe are part of an acid gneiss complex; the complex includes subordinate amounts of basic and ultra-basic gneiss (early basites) and also rocks of presumed metasedimentary origin (the Gleann Tulacha and Gruinard metasediments). Two hornblende schist bodies (the Beinn Airigh Charr and Gruinard basites) are intimately associated with the metasediments.

Members of a suite of basic igneous rocks (the Scourie dykes) have intruded the gneisses, early basites and also the Gruinard metasediments and basite; the chronological status of the Gleann Tulacha metasediments and Beinn Airigh Charr basite is in doubt since no member of the Scourie dyke suite intrudes them. All of the basic igneous rocks have been metamorphosed and converted into amphibolites.

Petrological variation within each of the main rock groupings is more a function of the metamorphic fabric domain in which a rock occurs than of pre-metamorphic lithological heterogeneities. Presentation of detailed petrological descriptions is therefore based upon the metamorphic fabric sequences recognised, attention being focussed upon shape rather than orientation fabrics. These fabric sequences are used for purposes of structural correlation.

Structural sequences are also established using the evidence of interfering fold sets and the structural relationships between members of the basic dyke suite and the country rocks. Dyke intrusion involved at least three phases of injection; these are however envisaged as stages in a single protracted event. The period of dyke intrusion is therefore used as a stratigraphical marker within the complex.

Structural correlations based upon fabric criteria are consistent with the hypothesis that dyke intrusion was a single protracted event. Development of the complex is therefore considered in terms of a pre-dyke (Scourian) complex and a post-dyke (Laxfordian) complex. Deformational events D2, D3, D4 and D5 have been recognised in the Scourian complex whilst D6, D7 and D8 events affected the Laxfordian complex. The original nature of the S1 surface is unknown.

Most of the rocks show evidence of metamorphism in amphibolite facies, although evidence is cited which implies that the M3 event was, in part, in granulite facies. This pre-D4 high-grade metamorphic complex is correlated with the Badcallian (Park 1970), whilst later Scourian events are considered to be of Inverian age.

A detailed geometrical analysis of the small-scale structures is presented. In addition, the areas mapped permit the study of parts of three large-scale Lewisian structures, namely the Carnmore antiform, the Letterewe synform and the Tollie antiform. The N.E. limbs of the Carnmore and Tollie antiforms are considered to be large-scale Inverian structures, whilst the S.W. limb of the Carnmore antiform and the adjacent Letterewe synform are of Laxfordian age.

The metasediments neither contain any evidence of the Badcallian fabrics nor show the effects of pre-Inverian migmatisation, apparent elsewhere in the complex. It is therefore concluded that the metasediments were originally deposited upon a Badcallian basement, but were involved in Inverian structural and metamorphic events. Both groups of metasediments occur at similar structural levels and are associated with large hornblende schist bodies. It is thus likely that the metasediments are stratigraphically equivalent and that the hornblende schist bodies probably represent post-Badcallian, pre-Inverian meta-volcanic assemblages.

29 Samples of dyke material were analysed for major elements using "wet" techniques; 27 of these samples were analysed for Ni, Cr, Ba, Sc, V, Sr, Co, Zr and Cu by emission spectroscopy. The results of these geochemical analyses are presented. It is concluded that the chemical variation exhibited can be explained in terms of the differentiation of a magma having tholeiitic affinities. Igneous structures in the dykes are discussed with respect to possible differentiation mechanisms.

Consideration of the dyke fabrics and the structural relationships between dykes and country rock leads to the conclusion that the dykes were emplaced into a hot, but cooling, Inverian complex in which the Inverian structures exerted considerable control over dyke emplacement.

CHAPTER I

INTRODUCTION

A. HISTORY OF PREVIOUS RESEARCH

The first systematic attempts at mapping and describing the Lewisian Complex of North West Scotland (Peach et al. 1907) were primarily concerned with the mainland outcrop, which forms an interrupted belt along the Western seaboard of Sutherland and Ross-shire.

Two major petrographical divisions of Lewisian rocks were recognised by these early workers:-

- (i) A "Fundamental Complex" of orthogneisses and metasedimentary crystalline schists.
- (ii) A series of igneous rocks, mainly of basic composition, which were intrusive in that complex.

It was observed that the basic igneous intrusions had been modified to varying degrees by earth movements, and that these earth movements had not affected the Torridonian sediments which unconformably overlies the Lewisian rocks.

The gneisses were classified according to their mineralogy and structure. On the basis of recognised gneiss types and the effects of the pre-Torridonian movements upon the basic intrusive rocks, three geographical regions were recognised within the mainland Lewisian outcrop, see Map 1. The "Central District" extending from a Scourie-Laxford line to Loch Broom, comprised grey pyroxene-gneiss with pyroxenites, hornblendites, pyroxene-granulites and garnet-amphibolites of the Fundamental Complex, with later basic intrusive rocks relatively unmodified by the pre-Torridonian movements. The districts to the North and South of the Central District were characterised by granular hornblende-gneisses and

biotite gneisses. Microcline augen-gneisses were stated to be common in the "Southern District" and rocks with presumed sedimentary origins were described in the neighbourhood of Gairloch and Loch Maree. "Terrestrial stresses" of pre-Torridonian age were said to have converted many of the later basic intrusive rocks into foliated amphibolites.

Sutton and Watson (1951) proposed a metamorphic history for the mainland Lewisian based upon the structural relationships of the basic dykes to the Fundamental Complex and the progressive metamorphism of the dykes. They regarded the Lewisian as made up of two metamorphic complexes. Their older, or "Scourian" complex, comprised the Fundamental Complex of Peach et al. (op. cit.) and was composed of gneisses which were considered to have a metamorphic and migmatitic, rather than wholly igneous origin. Metamorphism of at least part of the Scourian complex was recognised to be in granulite facies, and the dominant structural trend to be North-East.

Their younger, or "Laxfordian" complex, occupied the areas which Peach et al. (1907) recognised as affected by the post-dyke earth movements, and involved metamorphic reconstitution of the Fundamental Complex in almandine-amphibolite facies; a North-West-striking foliation was also imparted during the Laxfordian deformation. The distribution of the Scourian and Laxfordian complexes is shown on Map 1.

During the great interval of time which was imagined to have separated the Scourian and Laxfordian metamorphic events, the North-West-trending dolerite dykes were intruded as an anorogenic swarm. The effects of progressive Laxfordian metamorphism upon the dolerite dykes were summarised by reference to seven stages or steps (Sutton and Watson op. cit. pp. 252-254, 275-276).

Bowes (1962a, 1962b) and Wright (1962) challenged the assumption that there existed but one set of basic dykes, which could be used as a

time indicator enabling a distinction to be made between Scourian and Laxfordian events.

The work of Peach et al. (1907), O'Hara (1962) and Tarney (1963) also implied that the dykes of the Central District of the mainland are not all of the same age, whilst the studies of Park (1964), Bowes and Ghaly (1964), Bowes and Khoury (1965), Bowes (1968a, 1969) and Khoury (1968) seemed to provide a large body of data in support of as many as four suites of basic dykes which could be distinguished tectonically.

Park (1970) reviewed the above evidence and concluded (p. 388) that, "there is still no positive evidence in favour of more than two tectonically separated suites in any single part of the mainland Lewisian - nor is there any evidence against correlating these throughout the Lewisian". Moreover, there is no evidence against putting both suites into the "Scourie" dyke swarm.

Radiometric age determinations on the mainland Lewisian (Giletti et al. 1961; Evans 1964; Evans and Tarney 1964; Evans 1965; Evans and Park 1965; Moorbath, Welke and Gale 1969; Lambert and Holland 1972; and Moorbath and Park 1972) have recently been summarised by Park (1970) and Moorbath and Park (op. cit.). In general, the radiometric determinations bear out the broad chronology proposed by Sutton and Watson (1951) with Scourian rocks yielding dates ranging from c. 2,900 m.y. to 2,200 m.y. and Laxfordian rocks yielding dates ranging from c. 1,850 m.y. to c. 1,100 m.y. Radiometric age determinations on the dykes of the Central District, mainly by K-Ar methods (Evans 1964), led to the suggestion that the majority of the "Scourie" dolerites were intruded shortly before 2,190 m.y. whilst the emplacement of other dyke types may have been as late as 1,950 m.y.

O'Hara (1961, 1962) and Tarney (1963) argued that in the Central District, dyke emplacement occurred into the hot country rock of a waning

metamorphic episode, for which the term "Inverian" was proposed by Evans (1963). Evans (1964) and Evans and Tarney (1964) thought that the Scourian gneisses were older than 2,600 m.y. and that the biotite pegmatites, previously considered to be Scourian (Giletti et al. 1961) gave ages about 350 m.y. later. Evans (op. cit.) also established that the amphibolite-facies gneisses of the Central District, which had been folded on W.N.W.-E.S.E.-trending axes prior to the dyke intrusions, gave ages within the range 2,200 m.y. to 1,900 m.y. He considered that these amphibolite-facies gneisses were Inverian in age and suggested a date of c. 2,200 m.y. for this episode.

There is some confusion in the literature over the usage of the term "Inverian". In the sense of Sutton and Watson (1951), the Inverian is part of the Scourian complex which includes all pre-dyke events. Sutton and Watson (1969) defend the position of the dykes as stratigraphical markers between Scourian and Laxfordian chelogenic cycles, and place the Inverian in the Scourian cycle. A pre-Scourian cycle is also recognised by these authors (Sutton and Watson, op. cit.).

Bowes, however, (1968a, 1968b, 1969) regards the Scourian as an orogenic episode which includes all pre-Inverian events, whilst the Inverian is considered to be a distinct orogeny separated in time from the Scourian. Park (1970) proposed the term "Badcallian" for the granulite-facies metamorphic episode at 2,600 + m.y., and reserved the term "Inverian" for the c. 2,200 m.y. structural-metamorphic episode immediately pre-dating the emplacement of the "Scourie" dykes.

Attempts have been made (Evans and Park 1965) to relate radiometric age determinations to the Laxfordian sequence of polyphase deformation and metamorphism. Much of this earlier work has been superseded by the data available in Moorbath and Park (1972); three main events at c. 1,700 m.y., c. 1,500 m.y. and c. 1,100 m.y. are recognised

by these authors in the Southern District of the Lewisian.

Detailed structural studies of small areas of the mainland Lewisian have been undertaken, (Park 1964, 1969a; Ghaly 1966; Keppie 1967; Bhattacharjee 1968; Khoury 1968; Cresswell 1969; and Dash 1969) but have failed to produce overall agreement on the interpretation of the structural sequence.

A particularly controversial aspect of Lewisian geology appears to be the status of the metasedimentary outcrops of the Southern District of the mainland. Horne (in Peach et al. 1907, p.40) described crystalline schists having affinities with sedimentary rocks which lie in "compound synclinal folds of the Lewisian gneiss"; these compound synclines are South-East-trending structures. Horne (op. cit.) also stated that there is no clear evidence to show that the gneiss is intrusive into the altered sediments. However, he considered that the intimate association of gneiss and metasediment suggested that the gneisses may be intrusive into the metasediments.

Sutton and Watson (1951) considered that the material subjected to Laxfordian metamorphism consisted of pre-existing rocks of the Scourian complex, (reasoning vindicated by the work of Moorbath et al. (1969)) but also suggested that the Loch Maree metasediments may have been deposited upon the Scourian basement, prior to Laxfordian deformation.

Park (1964, 1970) considers that the Gairloch metasediments are post-Badcallian and pre-Inverian, but states (Park 1970, p.391) that "No firm evidence has been published concerning the relationship of the sediments to the Inverian". Bowes (1968a, 1969), on the other hand, considers that the Loch Maree sediments are in part pre-Inverian, but also incorporate post-Inverian, pre-Laxfordian sediments. The fundamental difficulty concerning the chronological status of the Loch Maree metasediments is that the "Scourie" dykes do not appear to have intruded

them.

Gunn (in Peach et al. 1907 pp.187-189) described possible metasedimentary rocks which occur in a narrow outcrop in the Gruinard district, and which pre-date the intrusion of the basic dykes, now epidiorites. Tilley (1951) considered, however, that these so-called metasedimentary rocks were not in fact metasediments but developed in a belt of metasomatism and silicification in the complex.

B. AIMS OF THE PRESENT STUDY

It is clear that the present study is set against a back-cloth of considerable previous research into the Lewisian complex, research however from which some widely divergent conclusions have emerged.

One salient feature apparent in most studies of Lewisian rocks is that the Lewisian complex has been subjected to polyphase metamorphism and deformation. Any study, therefore, first needs to establish a detailed sequence of structural and metamorphic events. It is also clear that the "Scourie" dykes play a critical role in the unravelling and interpretation of such sequences.

The present study, therefore, attempts to establish a structural and metamorphic sequence within a relatively small tract of Lewisian outcrop, and to examine the relationships between the gneisses of the Fundamental Complex and the basic dykes which have intruded them.

The areas selected for study were originally mapped by Gunn and Clough (Peach et al. 1907 pp.172-252) and lie in the northern parts of the Southern District of the mainland, see Map 2. They include tracts of both the Gruinard and Gleann Tulacha metasediments (Peach et al. 1907 op. cit.) whose chronological status is in doubt.

The choice of area also allows the study of parts of two large-scale structures, the Carnmore antiform and the "compound" Letterewe

synform, first described by Horne and Clough (Peach et al. 1907 pp.39-40 and p.193).

It was further hoped that mapping on both sides of the Loch Maree fault would enable structural and metamorphic correlations to be made across this feature and permit the sequences of geological events established on the northern side of the fault to be correlated with recent work to the south. Map 2 illustrates the location of these major structures and areas recently mapped.

CHAPTER II

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CHAPTER II

METHODS AND ORGANISATION

A. INTRODUCTION

Despite the keen observations and attention to detail on the part of the Survey workers (Peach et al. 1907) no detailed structural or metamorphic sequences were proposed for the Lewisian complex; since this is considered pre-requisite to any synthesis of an area which has experienced polyphase deformation and metamorphism, the compilation of lithological and structural geological maps, based upon detailed field observations, and complemented by petrographical and structural analysis is essential. A total period of twelve months fieldwork was undertaken between the summers of 1968 and 1971, within the areas detailed on Map 2.

Geologically it is convenient to consider the mapped areas in terms of four sub-areas; Map 2 illustrates that these form three geographical units. The northern unit has been termed the Creag Mheall Beag area and the westernmost unit is the Poolewe area. A belt of poor exposure extending eastwards from Kernsary farm provides a convenient dividing line for the remaining unit; north of this line is the Kernsary area, whilst to the south is the Beinn Airigh Charr area.

1. Physiography

The quality of exposure varies throughout the areas studied. In the Creag Mheall Beag area exposure is excellent; this, combined with a thousand feet range in relief with a summit culmination of ca.1200 feet, provides ample scope for study in three dimensions.

Exposure in the Poolewe area is likewise good where Meall a' Cliuth and Boor Hills rise over 700 feet and 500 feet respectively above the shores of Loch Ewe.

In the Kernsary area, exposure is poor by Lewisian standards, but still good; there is plentiful outcrop between the numerous lochans and peat hags. The range of relief in this area is approximately 500 feet.

The Beinn Airigh Charr area is well exposed in the area of Creag Cairneasair and the lower slopes of Beinn Airigh Charr. Exposure of the Gleann Tulacha belt of metasediments is not as complete as was initially hoped, but much useful information was obtained from two stream sections and from small quarries associated with derelict lime kilns.

2. Definition of Terms Used

Most geological terms used here are applied in the sense of contemporary usage, as defined in modern geological dictionaries, (Challinor 1967). Terminology which is particularly important in the present study is defined here for purposes of clarity.

Amphibolite is a rock composed essentially of amphibole and plagioclase feldspar. Small quantities of other phases may be present.

Basite is used in the sense of Park (1966) for a metamorphic rock body of basic composition which has amphibolite mineralogy.

Foliation is defined in its North American sense and covers all types of mesoscopically recognisable S-surfaces of metamorphic origin, (Turner and Weiss 1963 p.97).

Gneiss is a coarse grained, foliated metamorphic rock. The foliation may be expressed both in terms of the preferred orientation of constituent minerals and of lithological layering.

Lineation is any kind of linear structure within or on a rock, (Cloos 1946).

Mylonitic is used to describe rocks resembling true mylonites, that is for rocks consisting of strained porphyroclasts within a finer grained recrystallised matrix in which a foliated structure is apparent.

Schist is a medium grained foliated metamorphic rock. The foliation is a result of the preferred orientation of constituent minerals, especially micas, and sometimes amphiboles.

S-surface is any kind of penetrative planar structure in rocks, (Sander 1911).

In addition, the terminology applied to fold descriptions is the same as that used by Ramsay (1967). Pitch and plunge are used in the sense of Phillips (1960). Migmatite terminology used is essentially that described by Mehnert (1968).

B. FIELD TECHNIQUES

1. Maps

Most maps were constructed on a scale of 1 : 10,560 using Ordnance Survey "Six-inch" topographic maps or air photographs of equivalent scale. Both lithological and structural maps were prepared. Detailed relationships between the Gleann Tulacha metasediments, the Beinn Airigh Charr basite and the gneiss complex were mapped on a scale of 1 : 3,500 using enlarged air photographs, (see Map 5B).

2. Lithological Units

Four main lithological groupings have been recognised within the areas mapped; these and the various constituent lithologies are listed in Table II.S. together with the common minerals recorded in each lithology.

a. The Gneiss Complex

The greater part of the areas mapped comprises acid gneisses of granitic and granodioritic composition. Subordinate amounts of basic and dioritic gneisses are present, whilst thin horizons of kyanite gneiss are extremely restricted in their development. The acid gneisses

frequently contain K-feldspar augen and may be further sub-divided into massive and banded varieties.

For mapping purposes, distinction was made only between acid and basic gneisses, since the various gneiss types are not capable of rigorous definition, for instance in Plate II.1, banding is faintly discernible despite a relatively massive aspect. In addition the complex interdigitation and gradational contacts between the various acid gneiss units makes it impossible to represent this variation on the selected scales of mapping.

In reality the distinction between acid and basic gneisses is sometimes one of degree, since basic gneisses may be traced into areas in which there are abundant small basic inclusions contained within an acid gneiss host, resulting in a rock whose overall composition is dioritic.

b. The Basic Dykes

The basic dykes which intruded the gneiss complex have had most of their original mineralogy effaced, and are now reconstituted in the form of amphibolites.

c. The Metasediments

These are rocks of presumed sedimentary origin (Peach et al. 1907), which occur in two narrow outcrops. One of these, the outcrop of the Gruinard group, was first described by Gunn (Peach et al. 1907, pp.187-189) and comprises quartzites and mica schists. The other forms part of the Gleann Tulacha belt (Clough, in Peach et al. 1907, pp.235-236); thin interdigitating, laterally impersistent sheets of quartzites, mica schists, marbles, calcareous schists and calc-silicate schists are included within this grouping.

d. Beinn Airigh Charr and Gruinard Basites

Two hornblende schist bodies have been distinguished from the foliated amphibolite dykes. Both of these bodies are closely associated with the outcrop of the metasediments, (see Maps 3A, 5A and 5B).

The Beinn Airigh Charr basite is spatially associated with the Gleann Tulacha metasediments, whilst the Gruinard basite is a garnetiferous amphibolite associated with interbanded metasediments.

3. Specimen Collection

In total, over 700 hand specimens were collected, the field orientation of many of these specimens was clearly labelled according to the recommendations of Turner and Weiss (1963, p.85), in order to assist in petrographical analysis.

4. Measurement of Structures

The attitude of planar and linear structures was measured in the field by means of a Brunton clinometer. Most of the measurements recorded on the structural maps presented represent arithmetic mean values of several measurements made upon the respective structures.

A variety of penetrative and non-penetrative structures was measured. The most commonly measured penetrative planar structures include foliation surfaces and small scale fold axial planes. Penetrative linear structures recorded, included fold hinge lines, the long axis of boudins, quartzo-feldspathic rodding and mineral lineations - especially hornblende crystals displaying preferred linear orientation.

Lineations were measured on foliation surfaces; where such a surface was gently inclined the plunge amount and exact bearing were measured directly; with steeply inclined foliation surfaces, the amount of plunge of the lineation concerned was measured exactly, but the plunge direction was calculated by means of stereographic construction.

C. PETROGRAPHICAL ANALYSIS

Thin sections of more than 350 of the hand specimen samples were studied. Most of the rocks were sectioned perpendicular to the prominent lineation, if present; a few sections, cut parallel to the foliation, were also studied. Petrographical descriptions were made in the manner suggested by Turner and Weiss (1964, pp.207-215).

Measurements of 2V, extinction angles, and determination of the orientation of quartz $\{0001\}$ axes and mica $\{001\}$ cleavage were made following the instructions of Emmons (1943). Petrofabric plots of quartz and mica sub-fabrics are not presented; in practice it was discovered that the preferred orientation of micas was apparent without laborious Universal-Stage analysis, whilst the quartz sub-fabrics displayed several weak maxima and such broad scatter that their interpretation was extremely speculative. Most attention has therefore been given to shape rather than orientation fabrics, and to the sequence of fabric development.

The presentation of petrographical data (see Chapters III, IV and V) is organised according to fabric sequences established in each of the main lithological groupings described in section II.B.2; the reason for this is two-fold:-

(i) It avoids excessive repetition of petrographical information.

(ii) It provides a means by which structural and metamorphic correlations are made, both between and within the lithological units recognised.

Tables II.1-3 represent summaries of mineralogical modes for the material sampled. It is apparent from Table II.1 that the mineralogy of the acid gneisses reflects the fabric domain in which they occur; thus for those acid gneisses in which S5 is the dominant planar element,

hornblende is relatively important at the expense of biotite, compared with those acid gneisses in which S3 is the dominant planar element. Comparison of Table II.1a with Table II.1b indicates that the presence of K-feldspar and muscovite in most of the acid gneisses having dominant post-dyke fabrics is the main mineralogical contrast between the pre-dyke and post-dyke fabrics. Thus for the acid gneiss complex as a whole, the petrographical classification reflects the fabric classification. Initial petrological contrasts were apparently important since the S5 hornblende gneisses (Table II.1a) have a higher proportion of mafic phases in comparison to other acid gneiss types, and are strictly intermediate in composition.

Table II.2 illustrates that whilst the main petrographical distinction within the early basite bodies may be drawn between the mafic and felsic parts, there is a significant mineralogical contrast between pre-dyke and post-dyke melanosomes, the latter being relatively enriched in K-feldspar and biotite, and relatively impoverished in plagioclase, hornblende and epidote.

Tables II.3a-3b have not been organised according to fabric criteria because the large variation in rock types occludes variations expressing fabric contrasts. It is most convenient to consider these lithological contrasts as groups in which a recognisable sequence of fabric end members has been identified, rather than individual lithological details and the whole gamut of fabric permutations.

Petrographical description of the basic dykes is more conventional; a fabric sequence has, however, been established in the dykes themselves (see Chapter IV) and is used for purposes of correlation.

D. STRUCTURAL ANALYSIS

The mutual relationships of small-scale structures, linear, planar and curvilinear, were observed and recorded in the field (see

section II.B4) and a relative chronology of structural events was established by following a particular structure in the field and observing whether it affected, or was affected by, other structures. Structural measurements obtained were plotted on a Schmidt net, thus enabling analysis of any variation recorded. For clarity, some of the distribution plots were contoured by the Schmidt method.

Individual folded layers were analysed geometrically, in the manner of Ramsay (1967, pp.359-372) whilst, in a few cases, structural surfaces having complex geometry were considered by reference to constructed lineation pitch isogons (Elliot 1965), (see Maps 3D and 6B).

E. GEOCHEMICAL ANALYSIS

Geochemical analysis was undertaken of 28 samples obtained from members of the basic dyke suite; none of the basic dykes studied preserved its original igneous fabric; all are now amphibolites. The purpose of the geochemical analysis was, therefore, to enable identification of the initial igneous rock types by comparison with geochemically similar igneous rocks, and to provide a broad framework within which possible courses of evolution of the dykes could be discussed.

1. Sample Collection

Table II.4 is a list of localities sampled and briefly indicates the field relationships of the material collected. The choice and size of samples were in accordance with the recommendations of Wager and Brown (1960).

2. Preparation for Analysis

Weathered rind was removed and the samples were cut into 3 mm. sized cubes by means of a "Denbigh" rock splitter. These fragments were then passed through a "Sturtevant" jaw crusher.

At this stage it was necessary to make a choice between further crushing either by means of a Ni-Cr "Tema-mill", or by the use of a Roller crusher. Both of these methods presented the possibility of contamination by Ni and Cr; since it was intended to analyse for these elements, it was necessary to determine the contamination levels.

A sample of dyke material "GS" was split into two fractions after it had been passed through the "Sturtevant" jaw crusher. One fraction was then crushed to -240 mesh in a roller mill, and the other to -240 mesh in the "Tema-mill". Both fractions were analysed for Ni and Cr using Emission Spectrographic techniques. Arithmetic means of results for GS are shown in Table II.5, from which it is apparent that, *ceteris paribus*, the "Tema-mill" produces a significant level of Ni contamination.

In order to further verify these findings, and also to check the contamination levels produced in the roller mill, the experiment was repeated for two further samples, GM and GN. A three way split was made for these samples, and the third fraction was crushed to -240 mesh by means of agate crushers, not available in the Keele Department. The results of Ni and Cr analyses for these specimens are also presented in Table II.5.

It is apparent that the Ni contamination produced in the "Tema-mill" is extreme and is coupled with a limited amount of Cr contamination. However, there seems to be only a minimal amount of Ni and Cr contamination produced during the crushing process in the roller mill, and on the basis of these findings all the samples of this geochemical survey were crushed by means of a "Wardell" roller crusher. Each sample was taken to -240 mesh and, before analysis, each powder was dried at 120°C overnight in order to drive off hygroscopic water.

3. Methods of Chemical Analysis

Solutions A and B and Standard Solutions were prepared,

following the instructions of Riley (1958).

SiO_2 , Al_2O_3 , total iron as Fe_2O_3 , P_2O_5 , and MnO were determined spectrophotometrically (Riley, op. cit.) using a "Unicam SP.500" optical spectrophotometer. The optical density of the standards used was checked against Riley's recommended values.

Na_2O and K_2O were determined by means of an "EEL" flame photometer (Riley op. cit.).

FeO was determined by visual titrimetric methods using potassium dichromate as the indicator (Shapiro and Brannock 1962).

CaO and MgO concentrations were ascertained using a "Southern Analytical A1750 Atomic Absorption Spectrophotometer" (Walsh and Howie 1967).

Each series of analyses made contained an inter-laboratory standard as a check upon analytical accuracy. For major element analyses, two standards were used, namely:-

BCR-1, the American diabase standard.

BL3571, the Bristol amphibolite standard.

Table II.6 lists the results obtained for these standards.

Concentrations of Ba, Cr, Sc, Sr, V, Co, Cu, Ni and Zr were measured by emission spectrographic techniques, following the standard procedures adopted in the Geology Department Laboratories at Keele University. The spectrograph used was a Hilger Large Quartz Spectrograph, type E742; spectral line intensities were measured with a Joyce-Loebl Microdensitometer, Mark 3B.

Inter-laboratory standards BCR-1, BL3571 and KUM-1, the Keele "greenstone" standard, were used as checks upon accuracy.

4. Calculation of Results

C.I.P.W. and Molecular Norms were calculated by computer using programmes available for this purpose in the Keele Computer Centre. The

programme available for C.I.P.W. norms is an Algol version of Kelsey's (1965) method.

F. DISTRIBUTION OF THE MAIN ROCK GROUPS AND OF THE BROAD STRUCTURAL FEATURES OF THE AREA AS A WHOLE

These are illustrated on the large folder map incorporated at the end of Volume 2.

In the Creag Mheall Beag area, the acid gneiss complex includes numerous pods and lumps of basic and dioritic composition. The prominent, steeply dipping gneissose banding is folded by folds which have steep north-east-dipping axial planar foliation. A narrow W.N.W.-E.S.E.-trending outcrop of presumed metasedimentary rocks, the Gruinard metasediments, are intimately associated with the Gruinard basite; both metasediments and basite have a dominant north-east-dipping foliation, parallel to that in the enclosing acid gneisses.

Basic dykes, intrusive in the gneiss complex, have also intruded the Gruinard basite and metasediments. The dykes usually display steeply dipping contacts, parallel to the dominant north-east-dipping foliation in the gneisses and metasediments.

In the Kernsary area, the dominant foliation in the gneisses assumes a less steeply inclined attitude as it is traced southwards, and it becomes sub-horizontally disposed in the areas immediately south of Meall na Meine; thereafter the foliation in the gneisses shows progressively increased dips towards the south-west, as it is followed southwards into the Beinn Airigh Charr area.

The foliations in the gneisses thus define a broad, antiformal arch, the Carnmore Antiform, which has a sub-horizontal N.W.-S.E.-trending hinge line. The basic dykes within this structure are, for the most part, concordant with the foliation in the gneisses. Those dykes on the south-west limb are typically more foliated than the dykes on the north-east

limb, and the foliation of the dykes in the Kernsary area is parallel, or sub-parallel, to that in the gneisses.

The Gleann Tulacha metasediments and Beinn Airigh Charr basite are arranged in a complex synformal structure, the Letterewe Synform, outcropping in the Beinn Airigh Charr area. The foliation in the basite and metasediments displays great variability in attitude; dips are usually moderate or steep, comparable with those in the adjacent acid gneisses.

The basic dykes do not intrude the Gleann Tulacha metasediments and Beinn Airigh Charr basite and occur only in the gneisses, usually in the form of foliated amphibolites and hornblende schists. Typically the dyke margins, dyke foliation and the dominant foliation of the gneisses are parallel in attitude.

The dominant foliation in the gneisses and dykes of the Beinn Airigh Charr area has been folded on both small and large scales (see Maps 5A, 5B). A large monoclinial fold affecting the foliation of the gneisses and dykes occurs also in the Kernsary area and extends northwards from Kernsary farm to Meall na Meine (see Map 4).

The gneiss complex in the Poolewe area, situated to the south-west of the Loch Maree fault, contains a greater proportion of hornblende gneisses and gneisses of dioritic composition, compared with the gneisses in the three areas described above. The basic dykes are more numerous and display a greater frequency of branching than those in the other areas; in addition there is a greater proportion of crush rock and pseudotachylite, particularly along the south-western edge of the area.

The dominant structural element in the gneisses of the Poolewe area is a steeply inclined, north-east-dipping foliation; basic dyke margins are generally parallel to this foliation and are only locally discordant. Most of the dykes have been converted into foliated

amphibolites, the foliation in the dykes being parallel or sub-parallel to that in the gneisses. Structurally, the Poolewe area represents a northern extension of the north-east limb of the Tollie Antiform.

G. THESIS ORGANISATION

The history of research into Lewisian rocks, (see Ch.IA) focusses attention onto one of the major problems in the study of Lewisian rocks, and indeed, of other basement gneiss complexes; the particular problem is that of structural correlation.

Structural correlation of metamorphic rocks, or for that matter any geological correlation which is not biostratigraphically based, necessarily involves some degree of ambiguity. Some Lewisian researchers have used the period of dyke intrusion as a time marker within the complex; others have correlated metamorphic structures and concluded that successive phases of dyke intrusion were separated by tectonic episodes, thereby challenging the rôle of the basic dykes as stratigraphical indicators.

Recently, Park (1969b) has reviewed and criticised the traditional usage of fold style, fold orientation and fold symmetry for purposes of correlation in metamorphic belts. An attempt was therefore made to recognise criteria which could be used for purposes of metamorphic correlation and thus to test the validity of using the basic dykes as a time marker within the complex.

The field mapping of structures essentially consists of following a particular structure and observing its detailed relationships with other structures; for example, a foliation may be traced and found to represent an axial planar structure associated with the folding of an earlier foliation; it may also be folded itself during a subsequent deformational episode. Difficulties would however be expected in those situations in which the later structures were developed parallel to earlier

structures.

During the progress of field mapping it was observed that the dominant south-west-dipping foliation in the gneisses on the south-west limb of the Carnmore antiform, had a different aspect compared with the north-east-dipping foliation forming the north-east limb of the structure; the former had a finer foliation and much less distinct gneissose banding. These differences were analysed microscopically and explained in terms of shape fabric elements.

It was also observed that the dykes on the south-west limb of the Carnmore antiform appeared more schistose and had different microscopic fabrics compared with the dykes in the Creag Mheall Beag area; moreover in this latter area it is possible to observe local discordance between the dykes and the foliation in the gneisses.

The reasonable conclusion to be drawn from these observations is that the dominant foliations in the gneisses on the respective limbs of the Carnmore antiform are different in age, and the different foliations in both dykes and gneisses may be recognised in terms of shape fabric elements.

Common shape fabric elements considered include:-

- (i) The shapes of individual grains and grain aggregates.
- (ii) The mutual relationships between porphyroblasts and matrix phases.
- (iii) The mutual relationships of matrix forming phases.

The hypothesis that different foliations may be identified on the basis of fabric elements developed was tested generally throughout the areas mapped. Structural correlations were made by studying the detailed relationships of the dykes and dyke structures with structures in the gneisses; these correlations were based upon the premise that the basic dykes could be used as stratigraphical markers. Structural

correlations were also made using fabric criteria. Comparisons made between the structural sequences deduced in these two ways resulted in neither fabric nor structural inconsistency.

The thesis is therefore organised according to the fabric sequences recognised, and since no evidence was observed refuting the hypothesis that the basic dykes constitute a stratigraphical marker within the complex, pre-dyke and post-dyke fabric sequences are presented in separate chapters.

Since the basic dykes do not intrude the Gleann Tulacha metasediments and Beinn Airigh Charr basite, fabric correlations of structures in these and structures in the gneisses may seem more tenuous; this apparent difficulty was overcome by extrapolation from a common structure.

Thus, for reasons stated in section II.C the somewhat unconventional presentation of this thesis is adopted. Successive generations of structures have developed under different metamorphic conditions and exhibit differences in areal extent and intensity of development. These differences have been recognised in terms of metamorphic fabric elements. Each of the fabrics described in Chs. III-V represents an end-member fabric recognised in each of the main rock types described in section II.B2; an almost infinite number of gradations is however possible between each of the end-member fabrics described.

Thus the structural and metamorphic correlations made in the sequel, are based upon structural mapping and microscopic fabric analysis; this approach seems justifiable empirically, but suffers the same limitations as all correlations which are in essence lithostratigraphical.

CHAPTER III

THE PRE-DYKE PETROLOGY OF THE COMPLEX

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F. APPENDIX

Kinking in M5 Kyanite

CHAPTER III

THE PRE-DYKE PETROLOGY OF THE COMPLEX

The broad compositional range in terms of the modal proportions of mineralogical phases present in each of the mapped rock units was presented in Chapter II (see sections II.B2 and II.C).

Detailed description of recognised pre-dyke fabric end-members and metamorphic mineral paragenesis is presented in this chapter. In practice, most specimens studied contained elements of more than one of the fabric end-members; indeed the sequence of fabric development recognised is based upon study of the mutual relationships of different generations of shape fabric elements.

A sequence involving nine deformational episodes has been recognised in the complex (see Chapter VI); fabric elements are labelled in a manner consistent with the deformational episode with which they are associated. The basic dykes were intruded between the D5 and D6 events (see Chapter IV); thus S5 and pre-S5 fabrics are pre-dyke in age, whilst D6 and post-D6 fabrics post-date the period of basic dyke intrusion. S3 and S5 fabrics are the most important pre-dyke fabrics recognised.

A. THE ACID GNEISS COMPLEX

1. The S5 Fabric

S5 is the dominant structural element developed in the gneisses; it is associated with extensive modification of earlier structures and fabrics and is considered to have exerted an important influence on the post-D5 structure of the complex.

South of Meall na Meine and north of the Loch Maree fault, S5 is usually considerably modified. North of Meall na Meine, S5

varies progressively in attitude from sub-horizontal to sub-vertical near the Gruinard River; dips are to the north-north-east.

S5 may be identified mesoscopically by the elongation of quartz folia, or by the preferred dimensional orientation of biotite flakes. An L5 lineation, representing the intersection between S3 and S5 is developed parallel to F5 fold axes.

Microscopically S5 is defined by preferred lattice and dimensional orientation of phases developed in M5. No gneissose or segregation banding of M5 generation was observed and in so far as S5 appears to be defined by gneissose banding, this represents earlier S-surfaces transposed parallel to S5.

Plagioclase (An 25-29%) typically forms an equigranular granoblastic mosaic with quartz (see Plate III.1a-b). Grains are xenoblastic or subidioblastic, having a mean diameter of 0.7mm., with an approximate size range of 0.4mm. to 1.5mm. Mutual interfaces are straight or slightly curved; irregular boundaries are most noticeable where twin lamellae are oblique to grain boundaries. Plagioclase-quartz interfaces are usually curved, well defined, both smooth and irregular.

Many plagioclase crystals show evidence of zonation; normal, reverse and oscillatory zonation may be observed within a single thin section. These effects are most apparent in those gneisses which have been strongly affected by post-S5 deformation and metamorphism. It is therefore considered that the zoned plagioclase crystals post-date M5.

Most of the feldspars are twinned; both albite and pericline twins are developed. Albite twins are more common, and using the criteria of Vance (1961), most twins are secondary glide twins.

The mean length-breadth ratio is 0.7 for sections cut normal to L5, and 0.6 in sections cut parallel to S5; thus crystals are

elongate in the plane of the foliation, and in the lineation direction.

Quartz occurs as xenoblastic grains. It usually contains trails of inclusions (unidentified). The mean diameter of quartz grains is 0.6mm., but there is considerable variation in size. The modal grain size in the quartz subfabric usually exceeds 0.4mm. Where individual quartz folia are mesoscopically visible, microscopic examination shows that they comprise quartz aggregates in which individual grains may exceed 3 mm. in their greatest dimension. Crystal margins are typically rounded to lobate, both smooth and irregular. Most grains are noticeably strained, being flattened in S5 and elongate in L5.

Biotite occurs both as single crystals and in aggregates. Aggregates have their greatest dimension parallel to S5. The modal grain diameter of basal sections is 0.5mm. although in coarser textured examples the mean diameter of basal sections is 1.5mm. with the largest flakes exceeding 4mm. diameter. The modal grain thickness, measured perpendicular to $\{001\}$ cleavage traces is 0.2mm. Most grains are subidioblastic. Crystal boundaries with other phases are distinct, straight where parallel to $\{001\}$, but ragged on $\{010\}$ and $\{110\}$ faces. Pleochroism with absorption is strong according to the scheme X - straw yellow, Y - pale brown, Z - greenish brown with $Z > Y > X$. Where present, biotite defines S5, both by lattice and dimensional preference (see Plate III.1a); this is less obvious however when the biotite occurs in aggregates.

Hornblende tends to be layer specific when present in excess of 10% of the mode. Hornblende rich layers may exceed 1cm. in thickness; typically they are 1mm. thick, with an average layer spacing of between 2mm. and 5 mm. The thicker hornblende rich layers usually have a wider spacing with strongly developed segregation of mafic and felsic

constituents.

Most crystals are xenoblastic or subidioblastic in form. The mean diameter of basal sections is 0.6mm. and the mean length of longitudinal sections is 2.5mm., although there are considerable variations in size. Generally there is a decrease in grain size associated with decreasing proportions of hornblende in the rock mode; in addition, strongly segregated hornblende gneisses tend to have coarser hornblende subfabrics.

Grain boundaries show variation from straight to lobate, smooth or slightly irregular. Mutual hornblende interfaces are curved or straight, smooth or slightly irregular. Textural evidence suggests that hornblende has in part overgrown the granoblastic feldspar fabric, which is preserved as rounded inclusions and enclaves within xenoblastic hornblende crystals (see Plate III.1b). L5 is sometimes defined by the elongation of hornblende, probably representing mimetic crystallisation, in view of the evidence presented above.

2V is large and exceeds 80° ; $Z^\wedge C = 18^\circ$; pleochroism is according to the scheme X - pale greenish yellow, Y - green, Z - deep blue green, with $Z > Y > X$.

Epidote is of several different generations. The precise chronology is difficult to determine. The general form of an epidote crystal comprises a rounded core of allanite, mantled by subidioblastic or idioblastic colourless epidote, which in turn is surrounded by a granular aggregate of yellowish green pleochroic epidote. These zones may not all be present, but the order of occurrence does not vary.

The largest grains exceed 0.7mm. in diameter. The modal grain size is 0.3mm. Most of the epidote is closely associated with the mafic minerals present; in particular a strong preference exists for a site at which biotite is replaced.

Kyanite forms large irregular discrete crystals, which show no preferred orientation and which cut across S5 (see Plate III.2a). Some crystals attain lengths of 7cm; most are subidioblastic and markedly poikiloblastic. Many samples also illustrate well developed kink bands, (see Appendix to this Chapter).

Chlorite of M5 generation is not common in the gneisses, being found mainly in the kyanite bearing variety. Crystals are subidioblastic, both stout and slender; the mean flake length is 1.5mm. Birefringence is high for chlorite. There is a tendency for chlorite to mimic the foliation defined by biotite, and several examples in which chlorite exhibits cross-cutting relationships with respect to S5, suggest that chlorite growth occurred during a static metamorphic phase.

Sphene occurs in accessory proportions and shows characteristic lozenge shape. The longer diagonal of rhombic sections has a mean value of 0.4mm. Sphene frequently occurs in association with biotite aggregates, and is often in the form of trails aligned parallel to biotite $\{001\}$ cleavage traces.

Apatite is also found in accessory proportions. It occurs mainly as discrete idioblastic crystals; basal sections rarely exceed 0.2mm. in diameter.

Zoisite usually occurs as discrete subidioblastic or xenoblastic grains. Basal sections rarely exceed 0.2mm. in diameter. Some zoisite crystals have an irregular mantle of pale yellowish green pleochroic epidote. Rare examples of zoisite outgrowths from idioblastic colourless epidotes having allanite cores were also observed. On the basis of this textural evidence it is considered that zoisite growth post-dated that of the colourless idioblastic epidote, but pre-dated that of the xenoblastic pale yellowish green variety.

Iron Ore of various types was observed in those gneisses having

S5 as the dominant planar element. The ore, for the most part, post-dates M5 and is not considered further in this section.

2. The Modified S3 Fabric

The S3 fabric has not been observed in an unmodified form in the area studied in detail; however, in the north east of the Creag Mheall Beag area the intensity of S5 wanes and it is from here that most of the petrographical information about S3 was collected.

Usually S3 represents a compositional banding in which there is segregation of mafic and felsic constituents. Felsic bands have a mean thickness of 0.75cm., and in mafic bands the mean thickness is 0.5cm. There is, however, considerable variation in the thickness of mafic and felsic layers and some bands attain thicknesses of several centimetres. At F3 fold closures the compositional layering is folded and S3 is represented by penetrative foliation; thus the S3 banding probably represents an earlier compositional layering, now mainly transposed.

Plagioclase (An 25-30%) is the dominant felsic mineral of these gneisses. It forms large xenoblastic grains, usually showing the effects of sericitisation, and typically containing numerous inclusions of which subidioblastic forms of clinozoisite are the most common; quartz blebs, small biotite flakes, epidote and other unidentified dusty inclusions were also observed. Most inclusions are less than 0.1mm. in diameter, although there is considerable size variation. The modal diameter of plagioclase crystals is 1.5mm.; some grains exceed 3mm. diameter. Mutual plagioclase interfaces vary from straight to irregular and stepped. Plagioclase-quartz boundaries tend to be rounded. Margins with biotite are straight, parallel to the biotite {001} cleavage, but ragged in other directions.

Many plagioclase crystals exhibit complex patterns of undulose extinction, partly resolvable in terms of strain effects, but partly due to mineralogical zonation. The zoning is normal and variation in composition across the zoned mantle is usually less than 5% An. The relatively calcic cores show preferential sericitisation (see Plate III.2b). Most grains have combinations of albite and pericline twinning.

Quartz occurs as xenoblastic grains containing trails and scattered unidentified dusty inclusions. The mean diameter is 0.7mm., but individual grains exceed 1.5mm. Quartz aggregates occur in some felsic bands which are relatively rich in quartz; most members of such aggregates are elongate parallel to S₅, producing the typical mesoscopically visible quartz folia which define S₅. Some grains exceed 2.5mm. in their greatest dimension.

In some domains in which quartz is less abundant irregular lobate forms are found interstitial with respect to the feldspar subfabric and mafic aggregates. Crystal boundaries vary from smooth to irregular. Undulose extinction is universal.

Biotite is the dominant mafic mineral of the S₃ banded gneisses. It most commonly occurs in aggregates of variable size (see Plate III.2b); some of these aggregates attain diameters in excess of 3mm., although the modal flake length is approximately 0.5mm. Concentrations of aggregated biotite are parallel to the S₃ banding, although individual flakes show no strong orientation preference. Most crystals have a subidioblastic form. Pleochroism with absorption is according to the scheme X - straw yellow, Y - brown, Z - greenish brown with $Z > Y > X$.

Hornblende is uncommon in the S₃ banded gneisses. Most forms are xenoblastic or subidioblastic. Elongate sections have a mean length of 1.5mm. Basal sections have a mean diameter of 0.8mm. Most crystals are markedly poikiloblastic; grain boundaries tend to be

straight parallel to $\{110\}$ cleavage traces, but lobate, smooth or jagged in other directions. Hornblende is usually nucleated upon biotite aggregates and shows no obvious preferred orientation. Subidioblastic forms were observed in cross-cutting relationships to both the S3 and S5 foliations. 2V is large, $Z^{\wedge}C = 19^{\circ}$. Pleochroism is according to the scheme X - greenish yellow, Y - green, Z - bluish green with $Z > Y > X$.

Epidote is generally associated with the mafic aggregates occurring as a colourless, weakly pleochroic variety which develops subidioblastic forms. Elongate sections have a mean length of 0.3mm., basal sections have a mean diameter of 0.15mm. Occasionally epidote has a core of metamict allanite.

Zoisite occurs quite commonly in the S3 banded gneisses. In felsic domains, fewer but larger zoisite crystals are developed than in adjacent relatively mafic domains. The modal grain size is similar to the values quoted for epidote (above). Crystal forms are subidioblastic. Zoisite crystals were occasionally observed with thin coronas of weakly pleochroic, strongly birefringent epidote.

Sphene occurs in accessory proportions as irregular xenoblastic grains and aggregates. There are considerable size variations, the largest crystals having diameters of 1mm. A strong locational preference exists for biotite aggregates.

Apatite occurs occasionally as small idioblastic prisms having diameters less than 0.1mm.

Iron Ore of various types occurs in small amounts.

3. The Unmodified S3 Fabric

Within the area studied in detail the S3 fabric has been modified to a greater or lesser degree; the unmodified S3 fabric may

be studied in S3 banded gneisses to the immediate north and east of the Creag Mheall Beag area.

Plagioclase (An 31%) occurs as fresh, interlocking equidimensional, xenoblastic crystals. The grain size is coarse and some crystals have dimensions in excess of 1cm. Crystal boundaries are smooth to jagged, stepped or slightly curved. Zoning is absent, although undulose extinction occurs as a result of strain. Both albite and pericline twins are developed.

Orthopyroxene occurs as fresh xenoblastic and subidioblastic forms which sometimes attain lengths of 1cm. in elongate section. Rhombic sections attain diameters of 3mm. Size variation is considerable. Crystals occur singly or as anastomosing aggregates. Crystal margins are smooth or slightly irregular, straight or rounded. Pleochroism is pronounced in shades of pink and pale green. 2V is large.

Clinopyroxene occurs as fresh xenoblastic forms which sometimes exceed 3.0mm. in length. Crystals occur discretely or in small aggregates. Crystal margins are smooth or slightly irregular, straight or gently curved. Pleochroism is weak in shades of pale green. 2V is large and positive.

Quartz occurs as irregular blebs and patches along interfacial boundaries of the other phases.

4. S5 Fabric Modifications of S3

Andesine, orthopyroxene, clinopyroxene and quartz are the principal minerals comprising the S3 fabric. The modification by S5 may be considered as a series of progressive stages, viz:-

(1) The least modified stage is represented by the reconstitution of orthopyroxene. Chlorite and biotite pseudomorphs after orthopyroxene have a corona of anthophyllite mantled by a deep greenish blue, strongly pleochroic amphibole. Clinopyroxene is fresh,

although similarly mantled with greenish-blue amphibole; plagioclase is slightly sericitised at this stage.

(ii) The second stage is represented by the reconstitution of clinopyroxene. A fine grained mosaic of intergrown biotite and quartz is succeeded on its outer margin by a variably developed zone of green biotite. Numerous small granules of exsolved iron ore are irregularly distributed throughout the area of a pseudomorphed grain. Biotite has a red-brown colour where closely associated with magnetite.

Orthopyroxene at this stage has been completely replaced. Aggregates of cummingtonite are mantled by zones of fine grained quartz and blue-green amphibole intergrowths, which in turn are succeeded by coronas in which coarser grained greenish brown-coloured biotite is developed. Numerous small iron ore grains are again present and have an irregular distribution.

Plagioclase at this stage remains relatively unaltered.

(iii) The third stage is the first recognised within the mapped area and involves the first microscopically identifiable reactions involving feldspar (see Plate III.3a). Complex quartz-feldspar intergrowths occur in domains separating M3-plagioclase xenocrysts. These xenocrysts typically contain numerous bleb-like inclusions of quartz. The mafic minerals at this stage comprise biotite and epidote aggregates.

(iv) In the fourth stage, the M3 feldspar xenocrysts are more sericitised and contain numerous inclusions, notably clinozoisite and epidote. Biotite and epidote aggregates represent the sites of M3 pyroxenes whilst the areas in between the M3 plagioclase xenocrysts comprise a finer-grained granoblastic fabric of quartz and feldspar, the latter being more typical of S5 (see Plate III.3b).

(v) In the fifth and final stage before the original S3 mineralogy is completely obliterated, relict feldspar augen occur in a

fabric which is otherwise entirely of S5 generation. Biotite aggregates are less conspicuous and individual flakes of biotite define S5 in a typical granoblastic quartz-feldspar mosaic. The relict feldspar augen are flattened parallel to S5; they are poikiloblastic and show evidence of replacement by microcline, a post-dyke effect (see section V.D5).

B. THE METASEDIMENTS

1. The Gleann Tulacha Metasediments

a. Calcareous Rocks

None of the samples studied possessed a sufficiently unmodified S5 fabric to justify detailed description. Phases which grew in M5 were muscovite, biotite, chlorite, plagioclase and magnetite. Quartz and calcite were probably involved in M5, but they have been deformed and recrystallised in post-S5 events, and all evidence bearing upon their M5 paragenesis has been destroyed.

Plagioclase (An 27%) Using the evidence of the relatively few specimens available for study, there appears to be a positive correlation between the amount of chlorite observed and the modal proportions of plagioclase feldspar.

Chlorite of a colourless variety, with polysynthetic twinning and relatively high birefringence was observed in some of the calcareous and calc silicate schists. Basal sections have a mean diameter of 0.5mm; forms tend to be stout.

Muscovite and Biotite occur in variable amounts and proportions and are usually homoaxially intergrown. The largest mica flakes exceed 5mm. in diameter.

b. Pure Quartzites

The S5 fabric comprises an irregular granoblastic mosaic with

S5 defined by the sub-parallel alignment of muscovite flakes, that are occasionally present.

Quartz has a mean grain size of 0.05mm.; the largest crystals rarely exceed 0.1mm. Most crystals are equidimensional, a few are elongate parallel to S5. Crystal margins are smooth, straight or slightly curved. Most crystals are unstrained. A lineation visible mesoscopically comprises elongate aggregates of granoblastic quartz.

Muscovite crystals have a mean length of 0.03mm. and a sporadic distribution. Rare examples of larger muscovite crystals attain lengths of 0.7mm. These large crystals are not always concordant with S5 and are considered to be related to a post-D6 event (see section V.D5b).

c. Impure Quartzites

None of the impure quartzites preserves an unmodified S5 fabric, however most of the strain of subsequent deformation appears to have been concentrated in the quartz crystals themselves, leaving the other M5 phases relatively unmodified.

Hornblende xenoblasts preserve some of the S5 fabric as an internal subfabric (see Plate III.4a). They usually form discrete poikiloblastic crystals, enclosing quartz and magnetite, and recrystallised in the static phase of M5. Prismatic sections have a mean length of 2mm.; basal sections have a mean diameter of 0.75 mm. Pleochroism with absorption obeys the scheme

X - pale yellowish green, Y - green, Z - deep bluish green with $Z > Y > X$. 2V is large and negative. $Z^{\wedge}C = 16^{\circ}$. Crystal boundaries with other phases, particularly quartz, are irregular.

Garnet also crystallised in the static phase of M5. It is a pink variety which appears almost colourless in thin section. Usually it occurs in clusters, elongated in planes parallel to S5.

Individual crystals are subidioblastic, somewhat sieved with quartz. The largest aggregates, normally comprising about 25 individuals, exceed 1cm. in length.

Biotite is relatively evenly distributed throughout the more impure quartzites as individual flakes or small aggregates. Forms range from subidioblastic to xenoblastic. The mean flake length is 0.5mm. Biotite crystals define S5 more clearly than any other phase present. Pleochroism with absorption is according to the scheme X - pale yellow, Y - brown, Z - deep brown with $Z > Y > X$. Pleochroic haloes are occasionally developed.

d. Mica Schists

A detailed description of the S5 fabric of the mica schists is not possible since it has been greatly modified by later events; M5 phases probably include staurolite, muscovite, chlorite and oligoclase.

Staurolite occurs as discrete subidioblastic, poikiloblastic crystals. The mean length of elongate sections is 1mm. Most crystals show well developed "pressure shadow" domains and polygonisation in response to post D5 strain (see Plate III.4b).

Muscovite crystals show evidence of D6 deformation (see Plate III.5a) and are aligned parallel to S5. An M5 age is therefore deduced for such crystals.

Chlorite is a colourless variety and is polysynthetically twinned with $\{001\}$ as composition plane. The birefringence is high for chlorite. It closely resembles the chlorite described in sections III.A1, C1, IV.B1a-b.

2. The Gruinard Metasediments

A lithological layering within this group has been deformed by F5 folds. Macroscopically this layering is defined in terms of

mappable units of mica schists and quartzites of variable purity, interbanded within garnetiferous amphibolites - the Gruinard basite.

Mesoscopically, interbanding of these lithologies is apparent; individual bands may be only a few centimetres thick, or defined by trails of M5 garnets.

a. The S5 Fabric

In view of the restricted distribution and intimate association of the Gruinard metasediments and basite, they are considered together in the following S5 fabric description. This fabric has been considerably modified by subsequent metamorphic and structural events, and its presence is thus inferred from relict subfabrics.

Garnet occurs as discrete idioblastic crystals attaining 2cm. in diameter. Crystals of quartz and magnetite are commonly enclosed; internal and external foliations are continuous and coplanar; it is thus concluded that the garnet is a static M5 phase.

Biotite defines a planar subfabric by the preferred crystallographic orientation of $\{001\}$ cleavage traces parallel to S5. Most crystals are subidioblastic; basal sections have a mean diameter of 0.7mm. Pleochroism with absorption is according to the scheme X - almost colourless, Y - pale yellow, Z - pale brown with $Z > Y > X$.

Hornblende Nematoblastic hornblende crystals have a mean diameter of 0.6mm. in basal section. Most crystals are subidioblastic. Pleochroism with absorption is X - pale green, Y - green, Z - bluish green with $Z > Y > X$.

Chlorite occurs as subidioblastic flakes having a mean diameter of 1mm. in basal section. Birefringence is relatively high, pleochroism is weakly developed with X - colourless, Z - very pale green.

Polysynthetic twinning is common, with $\{001\}$ as composition plane. The chlorite subfabric is decussate and post-dates both the planar biotite and nematoblastic hornblende subfabrics; it is considered to have crystallised during the static phase of M5. Post-crystallisation deformation and kinking is apparent in many specimens.

Magnetite forms xenoblastic and subidioblastic crystals having a mean grain size of 0.2mm. The magnetite subfabric appears to post-date that of chlorite, since magnetite appears to have replaced chlorite in a direction parallel to the chlorite $\{001\}$ cleavage. Elsewhere mimetic magnetite crystallisation has occurred parallel to S5.

C. THE BEINN AIRIGH CHARR BASITE

F5 folds were observed within the basite body although the original nature of the pre-S5 surface is unknown. Typically the S5 fabric comprises alternating layers of granoblastic quartzo feldspathic mosaics, and nematoblastic hornblende. F5 fold closures, visible mesoscopically, are less obvious microscopically, although it is apparent that S5 is in part a transposed pre-S5 compositional layering. For purposes of S5 fabric description the Beinn Airigh Charr basite may be conveniently subdivided into massive and laminated hornblende schists.

1. Laminated Hornblende Schists

Hornblende defines a well developed lineation, L5, upon S5 which comprises alternating layers, relatively enriched or impoverished in hornblende. Basal sections have a mean diameter of 0.07mm.; prismatic sections have a mean length of 1mm. although there are considerable size variations.

In many of the finely laminated hornblende schists, two distinct size ranges of amphibole are apparent, and the mean dimensions of the larger individuals is about five times those already described; these

larger hornblende crystals occur as discrete subidioblastic forms which have overgrown the dominant nematoblastic fabric of smaller crystals. The group of larger hornblende crystals displays random orientation and is considered to represent M6 crystallisation (see section V.A1).

The characteristic form of M5 amphibole is subidioblastic. Pleochroism with absorption is in accordance with the scheme X - pale greenish yellow, Y - green, Z - blue green, with $Z > Y > X$.

Quartz is confined to the more felsic laminae; it tends to be equidimensional, with smooth or slightly serrated, straight or slightly curved boundaries. The mean grain size is 0.2mm. Most crystals are slightly strained.

Plagioclase (An 31%) shows similar textural and size relationships as quartz; within mafic domains, however, in which quartz is frequently absent, the andesine occurs as small discrete xenoblastic grains. The feldspar is usually fresh; twinning is not common. Zoning, both reverse and normal, was observed in some grains. Zoning was most pronounced in those specimens in which the S5 fabric had been subsequently modified; it is therefore considered to be a post-M5 effect.

Chlorite has a restricted occurrence in the basite, but where it does occur it forms up to 20% of the mode. Chlorite-bearing schists tend to show a cruder lamination than do the other mesoscopically layered rocks.

Most crystals are xenoblastic, but show a strong preferred orientation fabric with $\{001\}$ cleavage traces defining S5. Basal sections of individual crystals exceed 1cm. in diameter. Polysynthetic twinning with $\{001\}$ as composition plane is common. Birefringence is high for chlorite. Crystal margins are irregular, straight or slightly curved.

Garnet is not commonly developed and usually occurs as discrete

individuals. Most crystals are idioblastic; twinning is occasionally apparent. The mean grain size is 4mm. Most crystals are sieved by quartz and magnetite which define an internal foliation, which is continuous and parallel to the external S5 foliation; the garnets obviously represent growth under static metamorphic conditions (see Plate III.5b); textural evidence is, however, inconclusive and growth may have occurred in the static phases of either M5 or M6.

Iron Ore of M5 generation occurs as platy crystals defining S5. The mean grain size is 0.3mm. The ore is magnetite. Most crystals are subidioblastic. In the granoblastic quartzo-feldspathic domains it is the iron ore which most clearly defines S5 (see Plate III.6a); however, where iron ore occurs as inclusions in chlorite, it is parallel to the chlorite $\{001\}$ cleavage (see Plate III.6b).

2. Massive Hornblende Schists

Hornblende is markedly xenoblastic and exhibits considerable range in grain size; basal sections of some crystals exceed 2mm. in diameter.

Quartz and Feldspar occur as granoblastic mosaics within discrete felsic domains; these domains are elongate parallel to S5, seldom, however, exceeding 2mm. in this direction or 1mm. measured at right angles to this direction. Within these felsic areas, the dimensions and textural relationships of the component quartz and feldspar crystals are similar to those described in section III.C1 above.

D. THE PRE-DYKE MIGMATITES

Three pre-dyke migmatitic phases have been recognised within the complex, the latest of which was coeval with D5.

Migmatitic events of post-D2, pre-D3 age and syntectonic to post-tectonic D3 age are well developed in the Creag Mheall Beag area.

In areas further south, the evidence of the earliest events has been masked by the combined effects of D5 and, in some cases, as many as three post-dyke deformations. However, in those southern areas where relatively unmodified S3 is occasionally found, the pre-D5 migmatitic events are represented, demonstrating that these events are not isolated occurrences restricted to the Creag Mheall Beag area.

1. Post-D2, Pre-D3 Migmatites

Most of the evidence of the earliest S-surface developed in the complex was observed in the early basite bodies; similarly most of the data concerning the earliest migmatitic event are derived from these early basite bodies.

Plate III.7a illustrates a typical phlebitic migmatite of this generation in which the trondhjemitic neosome cuts across the axial trace of an F2 fold of the amphibolite paleosome. In other localities, similar thin neosomes which appear broadly concordant with S2 have been folded in F3 and acquired penetrative S3 foliation.

2. D3 Syn-tectonic to Post-tectonic Migmatites

Evidence of these migmatites is more extensively preserved than in the case of the post-D2, pre-D3 migmatites, and in both cases this evidence is confined to members of the gneiss complex. Field relationships observed between migmatite neosomes and paleosomes are dependent upon the two main subdivisions of the gneiss complex into acid gneisses and early basites.

a. Early Basites

During D3, migmatisation of the early basite bodies involved the production of agmatitic and phlebitic structures. The neosomes of this generation of migmatites are thicker, more irregular and anastomosing than those already described (section III.D1). Most have penetrative

S3 foliation (see Plate III.7b).

The leucosomes of the post-D2, pre-D3 and D3 syntectonic migmatites petrographically resemble the modified S3 fabric of the acid gneisses (section III.A2), except for a lack of compositional banding and lower proportions of mafic minerals.

b. Acid Gneisses

Migmatization of the acid gneisses apparently post-dates D3 since thin neosome sheets of trondhjemitic composition locally cross cut S3, with which they are generally sub-concordant. The thickness of the neosome sheets rarely exceeds several centimetres and frequently these sheets contain feldspar porphyroblasts, the latter sometimes attaining several centimetres in length (see Plate III.8).

The D3 post-tectonic migmatization resulted in the production of calcic oligoclase augen which are usually elongate in the plane of S3 and overgrow the S3 fabric.

Many of the effects of the D3 post-tectonic migmatization in the acid gneisses have been modified by subsequent deformation and metamorphism; petrographically the neosomes have S5 or younger fabrics. Mafic minerals usually form only about 5% of the neosome mode.

c. Segregation Effects

Some of the gneisses in the northern part of the Creag Mheall Beag area, where S3 is the dominant foliation, have a coarse quartzofeldspathic fabric flecked with irregular mafic aggregates. Biotite is the dominant mafic phase, but hornblende and epidote are commonly present. The mafic flecks have a mean diameter of 5mm. Contacts between "flecked" gneisses and S3 banded gneisses are diffuse (see Plate III.9a). The transition from flecked gneiss to banded gneiss occurs parallel to the strike of S3 and does not involve any overall change in mineralogical proportions. Moreover the original forms of banding are sometimes

preserved in flecked gneisses (see Plate III.9b). It is therefore concluded that the flecked gneiss developed from the banded gneiss by some form of segregational process involving short range diffusion.

This effect is not only apparent in banded gneisses, but also occurs in an agmatized meladiorite body (see Plate III.10) where the mafic and felsic constituents are segregated in both the neosome and the paleosome.

The fabric of the segregated gneisses is similar to the modified S3 fabric described for the acid gneisses (section III.A2) and the segregation process is regarded, at least in part, as an M3 effect.

3. D5 Syn-tectonic Migmatites

The D5 syntectonic migmatites are developed over much of the area and it is possible to study the variations in intensity of migmatization and migmatite structures, both absolutely and relatively with respect to the paleosome. In many instances it is not possible to make categorical distinction between the effects of deformation, metamorphic differentiation and migmatization, due in part to the contemporaneous operation of these processes. For purposes of continuity, therefore, description of some of the deformational and metamorphic effects associated with the D5 migmatization are included in this section. A two-fold subdivision of the D5 syn-tectonic migmatites is made on the basis of paleosome type.

a. Early Basites

Gunn (in Peach et al. 1907 p.176) makes the following observations about the early basic rocks of the Gruinard District -

"(1) their foliation is parallel to that of the acid gneiss; (2) they have a north-east strike; and They seem to act like eyes or nuclei of resistance to the general flow of the acid gneiss, whether

we regard that as a fluxion or as due to mechanical movements."

In (1) Gunn is presumably referring to the foliation, here designated S₃, and in (2) he is apparently discussing the relative behaviour of contrasted rock materials during D₅. Thus whilst the D₅ deformation of the acid gneisses generally resulted in the production of relatively plastic folds and penetrative foliation, in the early basites, a variety of structures varying from undisrupted relatively close folds (Fleuty 1964) (see Plate III.11a) to intensely agmatized bodies having the overall form of a fold (see Plate III.11b). The neosomes which separate the fragments of agmatized paleosome are trondhjemitic in composition. In most deformed early basites, the dominant foliation in the melanosome is S₃, which, where the melanosome is strongly agmatized, shows varying degrees of rotation within the neosome.

Where early basite bodies have been involved in large-scale F₅ folding, fold closures preserve relatively unmodified S₃ fabrics. On the limbs of such folds, however, there is a progressive increase in the intensity of disruption and migmatization, leading in some cases to the development of schlieren structure (see Plate III.12); paleosomes have sigmoidal or twisted forms and the neosome forms an increased proportion of the rock bulk. Using such broad indicators as the relative amounts of disruption and the proportion of neosome with respect to the paleosome, it is concluded that the D₅ migmatization was most intense in the region of Meall na Meine, but decreased in intensity to the north and south.

(i) Leucosomes

The leucosomes associated with the D₅ syn-tectonic migmatization of the early basites are trondhjemitic and characteristically possess an S₅ fabric; in some examples quartz forms aggregates of large

xenoblastic crystals which sometimes attain diameters of 4mm.; the aggregates themselves sometimes exceed 1cm. in diameter, measured parallel to S5.

Large subidioblastic, but considerably sieved hornblende crystals have overgrown the S5 fabric of some leucosomes. Irregular quartz blebs form the majority of the inclusions. The largest hornblende crystals exceed 2cm. in length. Pleochroism with absorption is strong, X - pale yellowish green, Y - green, Z - deep blue green with $Z > Y > X$.

Biotite usually forms less than 2% of the leucosome mode and epidote is the dominant mafic mineral. The mafic proportion of the mode is usually less than 10%.

(ii) Melanosomes

The melanosomes in most cases form the paleosomes and exhibit a dominant S3 foliation. This is expressed by slight variations in mineral proportions and to some extent by a poorly developed nematoblastic fabric. Hornblende is the dominant mafic mineral; the mean diameter of basal sections is 2mm., but size variation is considerable. Most crystals are xenoblastic or subidioblastic, usually poikiloblastic and appear to have overgrown a fabric similar to that described in section III.A2.

Apart from the more obvious large bodies of basic rock which have been metamorphosed and migmatized, the early basic rocks include innumerable small inclusions of basic and ultrabasic rocks within the acid gneiss complex; indeed Gunn (in Peach et al. 1907 p.177) states that "The leading feature of the Fundamental Complex in this district may be regarded as the extraordinary abundance of the knots of basic material included in the gneiss.". These inclusions have a widespread but sporadic distribution, often arranged in trails; they vary in size

from several millimetres to several metres in diameter. Both ovoid and fold forms were commonly observed and most inclusions are elongate in the plane of S3. Some are foliated, but the foliation is usually oblique to that in the enclosing gneiss. Unfoliated varieties are usually ultrabasic.

The ultrabasic varieties commonly comprise monomineralic actinolite aggregates. Most crystals are subidioblastic or xenoblastic and the mean grain size is 2mm. Mesoscopically these have a pale green colour.

The basic types contain more feldspar. A blue-green coloured hornblende is the dominant mafic mineral and occurs as subidioblastic or xenoblastic, usually poikiloblastic crystals. Epidote occurs as irregular scattered inclusions, usually within plagioclase crystals, or as granular clusters along hornblende-plagioclase interfaces. Mesoscopically a dark green colour characterises the basic inclusions.

Irregular scales of biotite may be present in both ultrabasic and basic types. Biotite also forms an envelope about some inclusions in areas where S5 is strongly developed. In the Kernsary area, some of the basic inclusions are flattened in S5 and the biotite envelope constitutes the bulk of the inclusion.

Gunn (op. cit. p.178) regarded the basic inclusions as "products of segregation" or "included fragments of an older rock-system". On the basis of the distribution and field relationships of these inclusions, it is considered that they represent paleosomes of formerly more extensive basic and ultrabasic bodies, fragmented by the combined action of deformation and migmatization. Metamorphic segregation probably served to intensify pre-existing contrasts.

The existing form of these inclusions is considered to be a product not only of M5 syn-tectonic migmatization, but also earlier migmatitic phases; there is no evidence of any post-D3, pre-D5

introduction of basic material into the complex, nor is there any evidence to suggest that larger earlier basic bodies escaped the effects of D3 and older migmatisation. Plate III.13 serves to illustrate how basic inclusions may be developed as a consequence of D3 and D5 deformation and associated migmatisation.

b. Acid Gneisses

The field relationships associated with the D5 syn-tectonic migmatites imply regional variations in the intensity of this migmatisation.

In the Creag Mheall Beag area, near the Gruinard River, trondhjemitic neosomes are developed parallel to the axial planes of F5 folds (see Plate III.14). The neosomes occur in restricted horizons, usually those containing the greatest proportion of hydrous phases. The neosomes are not associated with any bodies of obvious igneous provenance, and are developed as planar sheets parallel to S5; paleosome-neosome margins are indistinctly defined. Thus, whilst there is an obvious structural control by S5 over neosome development, original compositional heterogeneities may also have been an important factor in migmatite development.

Plate III.15a illustrates the common situation in the northern part of the Kernsary area where S5 appears to exert even greater structural control over neosome development. The neosomes are formed along the limbs of asymmetric F5 folds; a preference is shown for those limbs in which the S3 foliation is more closely transposed into the S5 attitude. The neosomes are similarly trondhjemitic and have diffuse margins.

Locally, however, in the area of Maall na Meine, the D5 structures appear to be controlled by the D5 syn-tectonic migmatisation (see Plate III.15b); F5 fold forms lack continuity and show signs of

increased plasticity with the paleosome more generally pervaded by the neosome. This situation represents the greatest intensity of the D5 syn-tectonic migmatization and is located about 0.5km. north of the hill crest.

The petrology and fabric of the acid gneiss paleosomes is similar to that described in section III.A1. Precise petrological description of the neosome is not possible because of extensive post-D5 fabric modifications; in particular, the metasomatic introduction of microcline and the concomitant development of symplectitic muscovite (see section V.D5). Together these minerals may form 60% of the mode, giving a neosome that is strictly granitic rather than trondhjemitic.

Quartz occurs as coarse xenoblastic grains and forms up to 25% of the mode. Some crystals attain diameters of 2.5mm. and form irregular aggregates elongate parallel to S5. Crystal margins are lobate, both smooth and irregular.

Plagioclase (An 23) forms xenoblastic or subidioblastic crystals and constitutes about 10% of the mode. Grain diameters vary, usually within the range of 1mm. and 3mm. Most crystals show the effects of post-D5 modifications and replacement by microcline.

Biotite and various minerals of the epidote group may form up to 10% of the mode. Textural relationships exhibited by these minerals are similar to those described in section III.A1.

E. SUMMARY OF PRE-DYKE METAMORPHIC EVENTS

1. Pre-M3 Metamorphisms

There is no evidence relating to the original nature of S1. At F2 fold closures, S2 was observed as a penetrative foliation; thus whilst it is necessary to postulate that S2 is a surface developed under metamorphic conditions, the metamorphic grade of M2 remains obscure due

to the effects of subsequent deformational and metamorphic episodes.

2. The M3 Metamorphism

Relict fabrics associated with the M3 event have been traced northwards from the Creag Mheall Beag area into two-pyroxene-bearing gneisses, implying metamorphism in granulite facies.

In the areas studied in detail, however, any pyroxene which may have existed in the gneisses has been replaced, and coarse-grained refractory M3 feldspars and biotite aggregates provide the only clues of former high-grade M3 metamorphic fabrics.

The D3 episode involved production of an S3 fabric and the syn-tectonic migmatisation of the early basites; since migmatisation appears to be essentially an amphibolite-facies phenomenon it seems reasonable to equate this event with the prograde development of M3; the fact that the neosomes of the M3 syn-tectonic migmatites possess S3 fabrics (section III.D2a) lends support to the hypothesis that migmatisation occurred prior to the inferred granulite facies culmination of M3.

Another hypothesis may, however, be suggested in which the grade of M3 increased in a northerly direction, so that within the areas mapped in detail, granulite-facies conditions may have been approached or perhaps locally attained, but mainly the metamorphism was in amphibolite facies.

The syn-tectonic migmatisation of the early basites was not accompanied by any introduction of pegmatoid neosome into the enclosing acid gneisses, nor is there any evidence to suggest that anatexis occurred; this migmatisation is regarded as a product of mechanical anisotropies induced during D3 and metamorphic segregational processes occurring in M3, both in turn a product of the fundamental compositional anisotropies between the early basites and the enclosing acid gneisses.

The envisaged mechanisms operative are thus similar to those proposed by Reitan (1958). As the early basite paleosome is strained to the point of mechanical failure and rupture occurs, anisotropic pressure domains are generated within the body as a whole. Establishment of these pressure gradients induces "chemical activity gradients" whereby mineralisation occurs in the low pressure domains, thus forming the neosome. The new minerals favoured are those with high molal volumes such as plagioclase and quartz. Evidence in support of the operation of this process is the trondhjemitic nature of the neosomes which largely reflects the sodic nature of the S3 acid gneisses enclosing the early basite bodies, and from which most of the neosome material was presumably derived.

Post-D3 migmatitic events involved the metasomatic growth of calcic oligoclase augen, and the injection of trondhjemitic pegmatoid arterites (see section III.D2b).

3. The M5 Metamorphism

The phase assemblages described in sections III.A1, III.B, III.C and III.D3 are consistent with metamorphism in amphibolite facies. In the northern parts of the Creag Mheall Beag area S5 becomes decreasingly penetrative and there is progressively more evidence of S3 fabrics in a north easterly direction; this implies that the effects of M5 diminish northwards in the area of the Gruinard River, although there is little evidence to suggest that the grade of M5 decreases in this direction.

The D5 syn-tectonic migmatites are best developed in the areas north of Meall na Meine (section III.D3); M5 kyanite-bearing assemblages were observed about 100m. south of Meall na Meine whereas in the pelites of the Gleann Tulacha metasediments only staurolite is found. Thus it is possible to suggest tentatively that there is an increase in the grade

of M5 northwards from Loch Maree in the direction of Meall na Meine.

4. Migmatisation

There are no recognisable granitic plutons with which any of the migmatite neosomes may be associated and it seems probable that anatexis conditions were not generally attained. Further, evidence of migmatisation suggests neither anatexis nor the regional introduction of neosomes (e.g. see Plate III.11b, which illustrates how the neosome is confined to domains of agmatized early basite and does not penetrate the acid gneisses).

Detailed chemical studies of the acid gneisses were not undertaken, but certain parallels may be drawn between these and the Skagit gneisses, which Misch (1968) considers to be migmatized by processes involving metamorphic differentiation and metasomatism, rather than by any anatexis mechanism. Among the criteria presented by Misch which can also be applied to the present area are:-

(i) The composition and zonation of plagioclase crystals in the neosome and paleosome are broadly comparable, although in some cases the plagioclase in the neosome is slightly more sodic.

(ii) Potassic feldspar is often lacking in the migmatite neosomes; where it is developed, textural evidence suggests that the K-feldspar was introduced in a subsequent metasomatic event (see section V.D5). The generally trondhjemitic nature of the migmatite neosomes represents considerable deviation from minimum-melt composition expected in an anatexis situation.

However, in the area of Meall na Meine, where the D5 syn-tectonic migmatites appear best developed, textural evidence does not conclusively support a post-D5 metasomatic origin for the K-feldspar, and it is probable that the D5 syn-tectonic migmatites in this area were granitic rather than trondhjemitic; this, considered in association with

the type of migmatite structures developed in the Meall na Meine area (section III.D3b), may be indicative of localised anatexis.

(iii) A similar solid-state recrystallisation and deformation sequence is recorded in both neosome and paleosome; this implies a metamorphic rather than magmatic mechanism for migmatisation.

Consideration of all these factors leads to the conclusion that the pre-dyke migmatisations were accomplished by metamorphic segregational processes rather than by anatexis or regional introduction of granitic magma. Migmatisation of the early basites essentially involved disruption and the addition of trondhjemitic neosome, the obvious source of the latter being metamorphic segregations from the acid gneisses which enclose the early basites. Generally, therefore, the pre-dyke migmatitic events involved a redistribution of the salic components of the acid gneisses.

The metasedimentary units recognised are not migmatised, yet have been metamorphosed and deformed in D5. The two areas of metasediment outcrops are, however, remote from the Meall na Meine area, where the effects of the D5 syn-tectonic migmatisation are most apparent. The contrasted response to D5 deformation in the gneisses and metasediments may be of greater significance. D5 in the metasediments did not involve the disruption which is so characteristic of the early basites so that segregation of leucocratic neosomes in the manner described in section E2 (above) would be inhibited.

One further consideration concerns the intense post-dyke deformation which has occurred along and adjacent to the gneiss-metasediment contacts (see Chapters V, VI), so that it is possible that evidence of D5 syn-tectonic migmatisation of the metasediments may have been obscured by the effects of such deformation.

F. APPENDIX

Kinking in M5 Kyanite

Kink bands are often present in M5 kyanite, the form of the kink banding is illustrated diagrammatically in Plate III.16a.

The kink bands are best displayed in sections cut parallel to $\{010\}$; the $\{100\}$ cleavage traces have been rotated through 42° within each kink band, whilst in the crystallographic domains separating adjacent kink bands, bend gliding has resulted in apparent rotations of up to 12° for the $\{100\}$ cleavage traces. The mutual relationships of kink bands and bend glide features are such that the two phenomena appear to be genetically related.

Kinking occurs by translation gliding on glide planes; experimental deformation of kyanite shows that slip traces are parallel to $\{100\}$, external rotation occurs about $\{010\}$ and the slip direction is $\{001\}$ (Raleigh 1965). These conclusions are thus consistent with the evidence for the natural system presented above.

Using the geometrical model of Starkey (1968), the angle of external rotation can be found theoretically as follows:

In Plate III.16b T is the glide plane; it is normal to the plane of the figure and equivalent to the $\{100\}$ cleavage of kyanite. The glide line t lies in the plane of the figure; d is the spacing between two active glide lines considered. ABCD and A'B'C'D' outline the unit cells of the host crystal and kink band respectively. Since there is no phase change across the kink band boundary the two parallelograms are congruent.

Structural identity can only be maintained if DKB is equal to the lattice vector parallel to the glide line t, i.e. vt or an integral multiple of vt.

$$DKB' = MKN \quad (\Delta s_{A'B'N}^{CDM} \text{ are congruent})$$

$$\therefore MK = KN = \frac{1}{2} DKB'$$

$$\text{and } \tan \delta = \tan \epsilon = \frac{d}{\frac{1}{2} (n \cdot vt)} \quad (n \text{ is integer}) - \text{Eq. (I)}$$

Using the kyanite lattice parameters of Deer et al. 1966.

$$\beta = 104^\circ 2'$$

$$d = a_0 \cos (\beta - 90)$$

$$= 7.1 \cos 11^\circ 12'$$

$$vt = 5.57 \text{ \AA}$$

For $n = 1$ and substituting in Equation I

$$\hat{\delta} = \hat{\epsilon} = 68^\circ 12'$$

$$\omega \text{ (the angle of external rotation)} = 180^\circ - (\delta + \epsilon)$$

$$\therefore \omega = 43^\circ 36'$$

This is therefore in close agreement with the measured angle of external rotation.

The kinking is considered to be a D6 effect; M5 static kyanite occurs in areas in which D6 is the only significant post-M5 deformational event.

CHAPTER IV

THE DYKES

A. INTRODUCTION AND SOME PROBLEMS OF PRE-CAMBRIAN STRATIGRAPHICAL CORRELATION

B. THE DYKE SUITES

1. The First-Period Dykes

- a. First-Period Dykes of the Creag Mheall Beag Area
- b. First-Period Dykes of the Beinn Airigh Charr Area

2. The Second-Period Dykes

- a. Internal Structures of the Second-Period Dykes
 - (i) The evidence for multiple intrusion
 - (ii) Sub-horizontal layering in the dykes of the Creag Mheall Beag Area
 - (iii) Sub-vertical banding in the dykes of the Creag Mheall Beag Area
- b. Review of the Considered Differentiation Mechanisms
- c. Petrology of the Second-Period Dykes
 - (i) The Epidiorites
 - (ii) The Hornblende Schists
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CHAPTER IV

THE DYKES

A. INTRODUCTION AND SOME PROBLEMS OF PRE-CAMBRIAN STRATIGRAPHICAL CORRELATION

In many Pre-Cambrian terrains, the scarcity of Pre-Cambrian fossils, or the intensely metamorphosed and deformed nature of many of the rock units, renders classical biostratigraphical and lithostratigraphical correlation inapplicable. Attempts to establish stratigraphical sequences in Pre-Cambrian metamorphic regions have followed several courses.

Many authors have adopted the approach of Wegmann (1938) and Eskola (1948) and have studied the structural and metamorphic relationships between basement gneisses and schistose supra-crustal series. Comparisons made between basement and cover successions often indicate markedly different responses to the same geological events (Zwart 1963, Ramsay 1963) and this should be an important consideration in any appraisal of the validity of stratigraphical sequences established by this method.

Holmes (1951) has demonstrated a new approach to the problems of Pre-Cambrian stratigraphy by studying the pattern of radiometric age determinations with respect to interfering orogenic belts. Radiometric methods have been extensively used (e.g. Vinogradov et al., 1960, Polkanov and Gerling 1960), but "absolute" chronologies which rely on relatively large numbers of dated samples require careful correlation with established relative chronologies and cannot in themselves resolve the problems of Pre-Cambrian stratigraphy.

Teall (1907, in Peach et al. Ch.VII) describes the "Pre-Torridonian Intrusive Rocks associated with the Lewisian Gneiss"

and states that such dykes and sills are "of later date than the Fundamental Complex". Implicit in this statement, therefore, is the existence of a temporal indicator by which the geological events of the Fundamental Complex may be distinguished from those which have post-dated the intrusive rocks.

Sederholm (1926 p.32) likewise states, with reference to basic dykes, that "on the one hand they give the criterion for separating the older and younger Archean granites. On the other hand they furnish a material on which the intensity of the metamorphic changes can be measured."

Later workers, especially those interested in gneiss terrains, have used similar methods. Berthelsen (1961) thus extended and modified the work of Wegmann (1938), whilst more recent work by Wegmann and Schaer (1962) used three generations of basic dykes to establish a relative chronology in the Pre-Cambrian rocks of Southern Norway.

In the present study, using the methods of Sederholm (1926), a sequence of pre-dyke and post-dyke events has been established. Study of the post-dyke events alone has been made by reference to the dykes themselves. Criticism may be levelled at this approach on the grounds that there is controversy concerning the extent to which the dykes may be regarded as members of the same tectonic suite (see Chapter I); justification of this methodology is, however, twofold:-

(i) It does not result in any inconsistencies in the fabric analyses.

(ii) It has been successfully used by many other researchers into Lewisian rocks.

At least three suites of basic dykes are known to exist within the area of the present study. In the Creag Mheall Beag area the relationships between the three dyke suites are particularly well

displayed and the sequence of intrusion has been established; a chronological division of First, Second and Third-Period dykes is thus recognised.

It is important to emphasise, however, that whilst it is often possible to distinguish these suites petrologically, no structural and metamorphic episodes have been recognised as occurring in the time interval separating the three periods of dyke intrusion.

Most of the dykes studied have a north-westerly strike; with the exception of some dykes in the Kernsary area, most display steeply dipping contacts with the country rocks.

Three metamorphic events, M6, M7 and M8, have affected the complex subsequent to the intrusion of the dykes; these events have been registered to varying degrees within the dykes. All the dykes are now amphibolites and show the effects of at least one metamorphic event; none preserves an unmodified igneous fabric.

B. THE DYKE SUITES

1. The First-Period Dykes

The dykes of this generation are petrographically distinctive; three dykes of this group were studied in the Creag Mheall Beag area. Only two other dykes of this suite were observed, as narrow outcrops on Creag Cairneasair.

Gunn (in Peach et al. 1907 p.184) recognised the petrological individuality of this suite in the Gruinard area, "A second type is represented by a considerable number of soft green dykes, somewhat irregular in character and containing abundant mica. These are for the most part older than the epidiorite dykes. In the field they weather somewhat like ultra-basic rocks, and appear to be less acid than the ordinary basic type."

This quotation describes the essential characteristics of the First-Period dykes, although Gunn mistakenly identified chlorite as mica.

a. First Period Dykes of the Creag Mheall Beag Area

The three dykes studied have a metamorphic fabric but do not display well-developed planar structures. Dyke margins are somewhat finer grained and marginal facies tend to have more felsic minerals.

Hornblende forms between 45% and 75% of the mode. Large subidioblastic crystals exceeding 5mm. in elongate section are arranged in an interlocking network, set within contiguous aggregates of fine grained xenoblastic and subidioblastic forms. Lamellar twinning with $\{100\}$ as composition plane is common. Pleochroism with absorption is X - colourless, Y - pale green, X - pale blue green with $Z > Y > X$. $Z \wedge C = 19^\circ$.

Prismatic sections of the larger crystals display the effects of replacement by another amphibole. Replacement patches are elongate parallel to the $\{110\}$ cleavage traces of the hornblende host (see Plate IV.1a). The secondary amphibole shows weaker absorption and pleochroism; $Z \wedge C (= 15^\circ)$ is smaller.

Plagioclase usually forms less than 15% of the mode. Tabular felsic patches, attaining 1cm. in length and visible mesoscopically, comprise plagioclase aggregates and probably represent recrystallised igneous feldspar. Some tabular feldspars appear less recrystallised but contain abundant small acicular hornblende crystals aligned parallel to the $\{010\}$ cleavage traces; determination of the feldspar composition is therefore difficult.

In the recrystallised domains, most forms are xenoblastic, crystal margins are irregular and lobate and the mean grain diameter is 0.2mm. Most crystals are fresh. Albite and pericline twins are

infrequently developed. Zonation is normal and there is usually less than 5% difference in An content between the core and margin of an individual crystal.

Chlorite occurs as large subidioblastic flakes and aggregates and constitutes up to 15% of the mode. The diameter of basal sections frequently exceeds 5mm. Polysynthetic twinning with $\{001\}$ as composition plane is typical (see Plate IV.1b). Pleochroism is weak, X - colourless, Z - very pale green. Many crystals display the effects of post-crystalline flexing and kinking. $2V = 10^\circ$ and orientation is positive.

There is evidence of chlorite replacement by hornblende. Acicular hornblende crystals have penetrated some of the idioblastic chlorite $\{001\}$ faces, whilst small included xenoblastic hornblende crystals are elongate parallel to the chlorite basal cleavage traces.

Biotite is usually present in small quantities - less than 5% of the mode. It is associated with other mafic minerals and forms aggregates of xenoblastic or subidioblastic flakes. Basal sections have a mean diameter of 0.6mm. Pleochroism with absorption accords with the scheme X - buff, Y - yellowish brown, Z - reddish brown, with $Z > Y > X$. Biotite appears to have replaced hornblende; the $\{001\}$ cleavage traces of included biotite are often co-planar with the $\{110\}$ prismatic cleavage of host hornblende crystals.

Quartz shows considerable variation in its distribution and grain size. It sometimes constitutes more than 5% of the mode. Forms are xenoblastic and occur interstitially in both mafic and felsic domains.

Rutile usually comprises about 1% of the mode in the form of subidioblastic and xenoblastic granules; these have a mean diameter of 0.1mm. and rarely attain 0.2mm. in diameter. They are most commonly

included in hornblende in the mafic domains, but are also numerous in the recrystallised feldspar domains. In a few instances a thin corona of sphene mantles the rutile granules.

Apatite Idioblastic and subidioblastic forms are present in accessory proportions.

Pyrite cubes or subidioblastic crystals are occasionally present.

b. The First-Period Dykes of the Beinn Airigh Charr Area

These differ from their counterparts in the Creag Mheall Beag area by having a well defined planar fabric of hornblende crystals and feldspar lenticles.

Hornblende constitutes between 50% and 60% of the mode and occurs in planar aggregates. Most forms are subidioblastic. The mean diameter of basal sections is 0.4mm. Some crystals poikiloblastically include quartz blebs in their cores, but this is a less common feature in these dykes than in the First-Period dykes of the Creag Mheall Beag area. Simple or repeated lamellar twinning with $\{100\}$ as composition plane is commonly developed. Pleochroism with absorption is according to the scheme X - colourless, Y - pale green, Z - pale blue green, with $Z > Y > X$.

Plagioclase (An 36) usually forms about 35% of the mode. Within the feldspar lenticles, xenoblastic crystals are common; polygonal grains are abundant and albite and pericline twins are commonly developed. The plagioclase crystals are sometimes completely altered, but many are fresh; in these a compositional zonal arrangement is apparent. This zonation has an oscillatory nature. Idealised traverses from the centre of a crystal to the margin indicate normal zoning, reverse zoning and then normal zoning; a few crystals, however, show more than two changes of zonation trend. The mean composition of

fresh crystals has an An content of 36%; variations consequent upon zonation do not usually exceed 6% An content.

Chlorite rarely accounts for more than 10% of the mode; it forms subidioblastic flakes and aggregates having a sub-parallel disposition with respect to the foliation. Basal sections of individual flakes may attain 2mm. in diameter. Most aggregates comprise much smaller crystals and the mean diameter of basal sections is 0.5mm. Polysynthetic twinning with $\{001\}$ as composition plane is usually developed and there is much evidence of post-crystalline deformation in the form of kink bands or disruption parallel to the basal cleavage. Pleochroism is weak, X - colourless, Z - very pale green. Textural evidence indicates considerable replacement of chlorite by a pale reddish orange biotite, and also by prehnite and zoisite.

Biotite usually constitutes less than 5% of the mode. It is usually associated with other mafic minerals as a replacement phase. Most crystals are xenoblastic or subidioblastic. Basal sections rarely exceed 0.4mm. in diameter. Pleochroism with absorption is X - buff, Y - yellowish brown, Z - reddish orange brown with $Z > Y > X$.

Quartz usually forms less than 5% of the mode and displays considerable variation both in its distribution and grain size. Crystals are typically xenoblastic; lobate projections and corresponding embayments of crystal margins are common. Most crystals have undulose extinction as a result of strain.

Sphene Comparison with the First-Period dykes of the Creag Mheall Beag area indicates that xenoblastic granules which sometimes attain 0.2mm. in diameter have completely replaced rutile.

Zoisite Subidioblastic and idioblastic zoisite crystals are a common replacement product of plagioclase. The mean grain size is 0.1mm.

Apatite Idioblastic and subidioblastic crystals occur in

accessory proportions.

Microcline may constitute more than 10% of the mode and forms xenoblastic crystals. The mean diameter is 0.2mm. Most crystals are concentrated in small groups which occur in association with the plagioclase lenticles parallel to the foliation. This microcline development is considered to represent the effects of a post-dyke metasomatic event which affected the complex, and is considered more fully in section V.D5.

2. The Second-Period Dykes

Criteria for the identification of this suite were established in the Creag Mheall Beag area, where cross-cutting relationships of the three dyke suites are particularly well displayed. In the Kernsary and Beinn Airigh Charr areas it has not been possible to establish a sequence of dyke intrusion; however, consideration of the petrological features of these dykes has resulted in their assignment to the Second-Period group. Similar reasoning has placed the Poolewe dykes within this second group, a decision supported by the presence of Third-Period dykes which display intrusive relationships towards them (see Plate IV.2).

The dykes of the Second-Period suite comprise "epidiorites" and "hornblende schists" according to the definitions of Peach et al. (1907 p.89). "Epidiorites" are "plagioclase, hornblende rocks, with or without a mineral of the epidote group". "Hornblende schists" are equivalent to "foliated epidiorites".

a. Internal Structures of the Second-Period Dykes

Lithological heterogeneities are a characteristic feature of the Second-Period dykes. Much of the variation is attributed to igneous processes, rather than to the results of subsequent metamorphism.

(1) The evidence for multiple intrusion

Most of the dykes of this suite have margins which are appreciably finer grained than the corresponding central facies; and it is the chilled effects of one dyke facies against other facies of the same dyke which provide most of the evidence of multiple intrusion (see Plate IV.3).

(ii) Sub-horizontal layering in the dykes of the

Creag Mheall Beag Area

Succeeding the chilled marginal facies of some dykes in the Creag Mheall Beag area is a zone in which there is obvious separation of mafic and felsic constituents to produce a stratiform effect (see Plate IV.4). Individual layers may exceed 5cm. in thickness; most have a sub-horizontal attitude and dip towards the dyke centre. (A constant 20° south-easterly dip component has been subtracted from these calculations and to correspond approximately with the regional dip of the overlying Torridonian sandstone.) Such layered zones seldom exceed several metres in width and their contacts against other facies of the dyke are sub-parallel to the dyke margins.

Sub-horizontal mineralogical layering in basic and ultra-basic igneous rocks has been described by several authors (Brown 1956, Hall 1932, Hess 1938, Jones et al. 1960, Peoples 1936, Wager and Deer 1939) and has been attributed in part to the gravitational settling of crystals from a convecting magma. The form and structure of the banded facies within the dykes described here show similarities to some of the rhythmic gravitational layering described by these authors. Examination of individual layers reveals that whilst there is a gradation from mafic to felsic domains, the base of each mafic unit is more clearly defined than the base of the succeeding felsic unit, features which would be expected if gravitational settling of crystals had occurred, even if settling was

restricted to a single mafic phase.

Wager et al. (1960) have described textural criteria by which gravitationally-layered basic igneous rocks may be identified and classified, but since the dykes do not preserve unmodified igneous fabrics, it is difficult to apply these. However, no alternative mechanism by which such a regular stratification may be produced has been envisaged.

Wager and Deer (1939), Brown (1956) and Hess (1960), explained some of the features of rhythmic layering in terms of the action of convection currents within the magma chamber. However, convection currents are unlikely to have operated in intrusions as small as the dykes being considered.

Yoder and Tilley (1962) have demonstrated that high water vapour pressures suppress the crystallisation of plagioclase. Fluctuations in water vapour pressure could therefore have controlled the relative quantities of mafic and felsic phases, thus affecting the rate of accumulation of possible cumulus phases. Rhythmic layering in response to water vapour pressure fluctuations has been described for late-stage differentiates of granitic magmas (Jahna and Tuttle 1963). However, the relatively uniform thickness of the mineralogical banding in the dykes, combined with the relatively large number of rhythms, would necessitate a large number of regular fluctuations in water vapour pressure; this mechanism is therefore considered unlikely.

Wager (1959) argues that in basic magmas undergoing slow cooling, stable crystals nucleate when the magma is supersaturated in their components; crystal growth reduced such supersaturation, but alteration of the composition of the magma consequent on crystal settling may cause supersaturation in the components of other phases, thus leading to their nucleation and growth. Isolation of the second phase causes supersaturation of the components of the first phase, and so the process

may be continued to produce gravitationally differentiated cumulates. In a footnote, Wager (1961) suggests that the more complex crystal structures require a greater degree of supersaturation and cooling before nucleation occurs.

The feasibility of the gravity-settling hypothesis may be challenged by suggesting that there is no effective floor to the magma chamber upon which crystals could accumulate. However, a study of the mapped forms of the intrusions reveals that they have irregular shapes and often display branching or have small offshoots; it therefore seems probable that their shape in vertical section would show similar irregular form and, indeed, where different levels of a dyke are brought into juxtaposition by a fault, they can seldom be exactly correlated. Crystals gravitationally settling from the magma could therefore accumulate above gneissose screens or in dyke apophyses.

(iii) Sub-vertical banding in the dykes of the

Creag Mheall Beag Area

The central facies of the dykes which have been least metamorphosed display relict igneous textures, similar to the ophitic textures of unmetamorphosed dolerites and gabbros; relict lath-shaped plagioclases of igneous provenance are commonly visible mesoscopically.

The central parts of many dykes also show considerable variation in the proportions of their mineralogical constituents. Compositional heterogeneities frequently show a layered disposition which may have a folded form (see Plate IV.5a-b). Individual bands vary in thickness from a few centimetres to several metres. Banding and fold axial traces are oriented parallel to the dyke margins; thus in the Creag Mheall Beag area where the dykes are steeply dipping sheets, this banding makes a high angle with the sub-horizontal gravitational layering which it truncates.

Contacts between the mafic and felsic rock types are frequently sharp and the felsic domains are appreciably finer grained near to the contact (see Plate IV.6). (Similar banded structures have been observed in Second-Period dykes in the other areas studied; the banding does not always have a sub-vertical attitude, but is developed parallel to the dyke margin.)

The heterogeneities having folded forms are interpreted as earlier formed planar banding deformed either by the influx of fresh magma in the axial region of the dyke, or by the action of compressional forces exerted on the sidewalls of a partially consolidated dyke. Expulsion of intercrystalline liquid would serve to heighten existing lithological contrasts and lead to the generation of further differentiates by filterpress processes.

The planar inhomogeneities observed in the axial regions of several dykes (see Plate IV.5b) may represent extreme flattening of earlier formed banding in the least crystalline portions of the dykes; alternatively flowage differentiation of suspended crystals may be considered as a possible explanatory mechanism.

b. Review of the Considered Differentiation Mechanisms

Although the evidence in support of multiple intrusion is clear, the metamorphosed state of the dykes obscures much of the textural and mineralogical evidence which is necessary to test the proposed operation of gravitational-settling and filter-press mechanisms.

Upton (1964) has described internal structures in the Tugtuloq gabbro dykes of South Greenland resembling the sub-horizontal layering described here, and attributes them to the effects of magmatic winnowing of crystals and fluctuations in the partial pressure of volatiles. However, within the dykes studied here, the major lithological subdivisions have an approximately symmetrical distribution, and lithological contacts

are parallel, or closely parallel to dyke margins.

The greatest single control over the history of an emplaced magma is its rate of cooling; the form and distribution of the main lithological subdivisions within the dykes imply, therefore, that the dyke margins have been the surfaces of greatest heat loss. To explain the sub-horizontally layered basites as accretion products on the surface of greatest cooling would be an untenable hypothesis, since in the Creag Mheall Beag area this surface generally has a sub-vertical attitude. An idealised sequence of events succeeding the formation of a chilled border facies involves, therefore, the production of gravitational stratification in favourable localities and under quiet magmatic conditions; much of the stratification may, however, have been destroyed or deformed by subsequent influxes of magma or by the action of stresses upon the sidewalls of the dykes. Those domains, close to the dyke margins, where there was sufficient crystallisation of interstitial liquids to produce a coherent rock would be preserved. The sub-vertically disposed layering in the axial regions of the dykes may represent the consequences of flow lamination, or intense deformation of the least crystalline domains. Fig. IV.1 illustrates a diagrammatic section across a differentiated Second-Period dyke.

c. Petrology of the Second-Period Dykes

Considerable variation in fabric is exhibited between and within members of this suite, and a complete spectrum exists between foliated amphibolites or "hornblende schists" and the "epidiorites".

Mineralogical variation expresses itself mainly in terms of the relative proportions and forms developed by the two dominant mineralogical phases, hornblende and plagioclase.

For convenience, the petrological description of this group will be considered in terms of the two fabric end members, "epidiorite"

and "hornblende schist".

(i) The Epidiorites

These comprise unfoliated rocks in which remnants of the original igneous fabrics are preserved, whilst the present distribution of lithological heterogeneities closely reflects the initial igneous lithological variations.

Hornblende In banded and layered epidiorites, hornblende may constitute 95% of the mode of the mafic domains; normally, however, it comprises between 40% and 60% of the mode. Hornblende is usually concentrated into aggregates, visible mesoscopically (see Plate IV.6). The individual xenoblastic grains which constitute such aggregates are frequently smaller than 0.01mm. in diameter. With increased modification of the igneous fabric by subsequent metamorphic events, the hornblende aggregates assume the forms of discrete xenoblastic or subidioblastic hornblende crystals, which have a core of randomly orientated fine grained quartz and hornblende crystals succeeded by an inclusion-free mantle in optical continuity.

The mean diameter of the hornblende aggregates is 4mm. in the widest dykes. Pleochroism with absorption is according to the scheme X - pale green, Y - green, Z - bluish green with $Z > Y > X$.

Plagioclase rarely exceeds 5% of the mode even in the felsic domains of the layered epidiorites. It usually occurs as tabular laths which may exceed 5mm. in length. Grain boundaries are smooth, but irregular. Most crystals are turbid but have a thin mantle of fresh plagioclase which is normally zoned; such zoned mantles have compositions in the range 35% to 39% An and display albite and pericline twins. The turbid core domains probably represent the sites of plagioclase more calcic than the existing fresh mantles. The plagioclase subfabric resembles the pilotaxitic textures of gabbros and dolerites.

Biotite usually constitutes less than 5% of the mode. Most crystals are xenoblastic and occur as aggregates of interlocking flakes; such aggregates are concentrated about the margins of hornblende aggregates. The mean diameter of basal sections of biotite is 0.1mm. The pleochroic scheme is X - beige, Y - pale brown, Z - orange brown. Discrete xenoblastic biotite flakes occur within the felsic domains.

Quartz usually forms about 5% of the mode and occurs in association with the hornblende aggregates as small poikiloblastic blebs. Xenoblastic lobate quartz crystals commonly occur interstitially with respect to plagioclase laths.

Magnetite - Ilmenite intergrowths have skeletal habit and constitute up to 3% of the mode. Such irregular patches of intergrown ores attain diameters of 3mm. Thin coronas of sphene mantle the magnetite-ilmenite intergrowths.

Apatite forms subidioblastic crystals and occurs in accessory proportions. The mean grain size is 0.1mm.

(ii) The Hornblende Schists

Mesoscopically the most apparent feature of such rocks is a foliation defined by the parallelism of platy aggregates of hornblende and feldspar. Original igneous lithological heterogeneities have been flattened to impart a banded structure parallel to the foliation (see Plate IV.7).

Hornblende forms between 40% and 60% of the mode and occurs as aggregates of subidioblastic inclusion-free prisms. Crystal margins are smooth, straight or slightly curved. Mutual interference by adjacent grains has produced polygonal mafic subfabrics. Planar or linear orientation preference by hornblende defines the fabric. The mean diameter of basal sections is 0.5mm. although the range of variation is considerable. Pleochroism with absorption is according to the scheme X - pale green, Y - bluish green, Z - deep blue green with

$Z > Y > X$.

Plagioclase (An 28%) was rarely observed in an unaltered state. It usually constitutes between 35% and 50% of the mode. Most forms are xenoblastic. Crystal margins are smooth, straight or slightly curved, and the feldspar subfabric typically comprises polygonal grains. The mean grain diameter is 0.5mm.; in sections cut perpendicular to the lineation the mean breadth:length ratio is 0.5.

Biotite is not always present, but may form up to 10% of the mode. Most crystals are subidioblastic and occur as discrete grains which display a preferred orientation with the basal cleavage aligned parallel to the foliation. Most flakes are slender and the mean diameter of basal sections is 0.4mm. Pleochroism with absorption is according to the scheme X - pale greenish brown, Y - brown, Z - deep brown.

Sphene occurs as small granules and thin coronas about dispersed magnetite crystals. The magnetite crystals are xenoblastic and have a mean grain size of 0.1mm.

Apatite is present in accessory proportions. Most forms are subidioblastic; the mean grain size is 0.1mm.

d. Metamorphic Fabric Development within the Dykes

The development of hornblende schists and epidiorites from the original basic igneous rock of the dykes was accomplished in three metamorphic stages, M6, M7 and M8; deformational episodes associated with these metamorphic stages are labelled D6, D7 and D8 respectively. Each of these structural and metamorphic episodes shows variation both in the grade of metamorphism and in the areal extent to which it is developed.

(i) The S6 Fabric

Dykes which are considered to have been only slightly deformed in D6 are essentially epidiorites, but may have selvages of

hornblende schist. The reconstitution of the original igneous fabric of the dykes to produce unfoliated epidiorite is regarded as an M6 effect (see Plate IV.8a).

Dykes which have been more intensely deformed in D6 are schistose throughout, whatever their original thickness. A combination of D6 and M6 conditions has therefore produced thoroughly foliated hornblende schists (see Plate IV.8b).

Dykes which are intermediate in type between epidiorites and hornblende schists display particularly interesting plagioclase subfabrics.

Plagioclase in equigranular polygonal crystals displays compositional zonation, both reverse and normal. Oscillatory zoning is common and up to four changes of zonation trend were recorded for individual crystals; usually the outermost zones are normal. The mean composition for such plagioclase crystals is An 30% and the maximum range of variation between compositional zones is An 6% (see Plate IV.9a).

The significance of the zoned plagioclase crystals is not well understood. There is no evidence of a change in metamorphic grade between the epidiorites and the hornblende schists; the foliation in the latter, however, provides strong evidence of their deformed state. It therefore seems that deformation has been an important controlling factor over plagioclase recrystallisation. Such recrystallisation would of necessity involve annealing (cf. McLean 1964). Plate IV.9b illustrates the development of lath shaped feldspars into polygonal feldspar grains, a situation analogous to the assembly of crystallographic dislocations into sub-boundaries in annealed metals. Such polygonal feldspar grains act as nuclei about which further growth occurs until the lath shaped feldspar subfabric is eliminated.

Growth about a stable nucleus depends upon ionic diffusion

rates, which in turn are related to the metamorphic grade. It is therefore considered most likely that the observed compositional zonation of the plagioclase feldspar represents stages of growth in response to relatively slight fluctuations in metamorphic grade, superposed upon the main M6 event. Similar compositional zonation features in other metamorphic minerals have also been attributed to variations in metamorphic grade (Harte and Henley 1966, Hollister 1966).

Garnet in idioblastic crystals attains diameters of 5mm. It is usually inclusion-free and has overgrown S6. Garnet distribution is sporadic within individual dykes and within the dyke group as a whole. It is considered to represent a static M6 phase.

Biotite When present, its preferred orientation serves to define S6. Biotite is most abundant in the Second-Period dykes of the Kernsary area, within which it may constitute 15% of the mode. It occurs as discrete subidioblastic crystals and lenticular aggregates parallel to S6. The mean diameter of basal sections is 0.7mm.

Pleochroism with absorption accords with the scheme

X - pale greenish brown, Y - brown, Z - deep brown.

(ii) The S7 Fabric

All the dyke rocks in which this fabric has been recognised are hornblende schists. It is difficult to distinguish between S6 and S7 hornblende and plagioclase subfabrics; however, the S7 fabric can usually be distinguished on the basis of the epidote subfabric developed.

Epidote sometimes forms more than 10% of the mode and there is a strong positive correlation between the distribution of F7 folds of the dykes and the amount of epidote in the rock mode of the Second-Period dykes. M6 garnets, some of which were flattened in D7 parallel to S7, have been replaced by aggregates of subidioblastic

epidote. Epidote also occurs as discrete idioblastic and subidioblastic crystals, which appear to have replaced both hornblende and plagioclase. The mean grain size for the epidote subfabric is 0.1mm.

(iii) The S8 Fabric

F8 folding of the dykes was not associated with any neomineralisation. Existing hornblende and plagioclase subfabrics display evidence of mechanical degradation and fracturing. The quartz subfabric has been intensely deformed and a planar structure of mylonitic ribbon quartz has been developed..

The combined effect of the fabric-producing events is a complex sequence of mineralogical and textural readjustments which correspond closely to stages 2 to 5 in Sutton and Watson's (1951) schemes of increasing Laxfordian metamorphism.

(iv) Microcline-Bearing Second-Period Dykes

Some of the dykes of the Kernsary and Beinn Airigh Charr areas contain microcline, usually to the extent of less than 10% of the mode. Samples from some dykes, however, contain more than 30% microcline. Most microcline crystals are xenoblastic, some are equant and yet others are markedly inequant. The mean grain size is 0.7mm.

The development of microcline post-dates that of the S6 plagioclase subfabric; polygonal plagioclase crystals have been partially enclosed by amoeboid lobes of microcline. Some microcline xenoblasts contain numerous small inclusions of idioblastic hornblende; it seems likely, therefore, that hornblende was also crystallising at the same time as microcline since partial replacement of hornblende by microcline would be expected to produce xenoblastic bleb-like hornblende inclusions.

It is therefore concluded that microcline was introduced into the dykes after D6 but within the static phase of M6. Microcline in

the dykes was deformed in D8.

The development of microcline in the dykes is considered to be an effect of a potash metasomatic event. Detailed consideration of this is reserved for a later section (Chapter V.D5).

The development of microcline within the dykes appears to be associated with replacement of biotite. The extent of replacement is extremely variable and completely pseudomorphed biotite occurs within a few millimetres of fresh crystals. Penninite is the common pseudomorph although prehnite lenticles are quite frequently developed parallel to biotite $\{001\}$ cleavage traces. Epidote and zoisite are commonly associated with pseudomorphed biotite. Microcline development thus appears to be linked with a complex series of mineralogical readjustments, involving in particular the diffusion of K^+ , Ca^{2+} , Al^{3+} and Si^{4+} ions.

3. The Third-Period Dykes

Dykes of this generation were observed in the Creag Mheall Beag area; one other example was observed in the Poolewe area. There is considerable variation in dyke thickness and lithology between members of this suite. Individual dykes, however, have a uniform aspect and there are no obvious examples of mineralogical segregation. Relict igneous fabrics are finer-grained than in dykes of comparable width in either the First or Second-Period dyke suites. Dyke margins are also appreciably finer-grained than corresponding dyke centres.

Hornblende constitutes between 45% and 65% of the mode. In the centres of the widest dykes hornblende occurs as aggregates of xenoblastic and subidioblastic crystals displaying no orientation preference. The xenoblastic crystals have cores containing irregular poikiloblastic blebs of quartz and plagioclase; crystal margins, however, tend to be inclusion-free; the mean diameter of such

xenoblasts is 0.8mm. Many display complex replacement patterns parallel to $\{110\}$. The replacive mineral is a similar type of hornblende.

Felted masses of subidioblastic hornblende prisms are inclusion-free; the mean diameter of prismatic sections is 0.2mm. Elongate sections have a mean length of 0.7mm., although there are considerable variations in size. Simple and lamellar twinning is sometimes developed with $\{100\}$ as composition plane.

In the narrower dykes and in dyke margins, hornblende displays a planar subfabric of subidioblastic crystals. The mean diameter of basal sections is 0.4mm. The pleochroic scheme is X - pale green, Y - green, Z - bluish green with $Z > Y > X$.

Plagioclase (An 32% - 39%) usually comprises between 15% and 35% of the mode. Lath-shaped plagioclase crystals have been almost completely recrystallised or replaced; where recognisable they are usually very turbid, although compositional determinations made upon a few fresh crystals indicated An contents of 39% adjacent to sericitised cores and normal zoning of the fresh rim to An 32%. Combined albite and pericline twins are developed.

The mean length of plagioclase laths from the coarser-grained dyke facies is 1.5mm. Recrystallised plagioclase forms xenoblastic polygonal grains which display both reverse and normal compositional zonation. The mean composition is An 31% and adjacent compositional zones differ by up to 5% An. Normal zoning is more common than reverse; the occasional occurrence of reverse followed by normal zonation was recorded. The mean diameter of the recrystallised grains is 0.2mm; many appear untwinned, but combined albite and pericline twins are commonly developed.

In dyke margins plagioclase occurs as xenoblastic crystals

which have a mean diameter of 0.1mm.

Biotite was not observed in every sample of the Third-Period dykes, but in some it forms more than 10% of the mode. It occurs both as individual crystals and aggregates of several grains. Most are subidioblastic. The mean diameter of basal sections is 0.2mm. in dyke margin facies and 4mm. in the relatively coarse-grained facies of some of the widest dykes.

Discrete biotite xenoblasts attain diameters of 2mm. in the marginal facies of some dykes; some of these xenoblasts have been replaced by aggregates of prehnite and penninite. A weak orientation is displayed by the biotites of the dyke margins, which probably represents mimetic crystallisation parallel to existing planar structures. Elsewhere the biotite displays no preferred orientation. Most biotite is associated with the hornblende aggregates. Pleochroism with absorption is according to the scheme
X - beige, Y - pale brown, Z - orange brown.

Epidote Minerals of the epidote group are commonly developed in the Third-Period dykes and may constitute more than 15% of the mode. In coarse-grained facies the epidote minerals appear to have replaced plagioclase feldspar. Most crystals are xenoblastic or subidioblastic; they occur as discrete crystals less than 0.1mm. in diameter as granular aggregates and as irregular dendritic masses up to 1mm. in diameter.

Zoisite usually occurs as individual bleb-like crystals or small aggregates associated with recrystallised plagioclase laths.

Clinozoisite and epidote usually form the larger aggregates and irregular masses. Clinozoisite crystals are frequently mantled with birefringence increasing towards the crystal margins. Colouration is pale yellow green to neutral. Pleochroism is weak or absent.

In the fine-grained marginal facies granular and subidioblastic epidote crystals have a mean diameter of 0.05mm. and are evenly distributed within these rocks.

Quartz usually comprises about 5% of the mode. It is markedly xenoblastic, forming small bleb-like inclusions in hornblende crystals and larger irregular patches in the interstices between other phases; these patches rarely exceed 1mm. in diameter; they tend to have lobate projections and invaginations. . Some crystals are strained.

Sphene forms up to 2% of the mode. Irregular granular aggregates attain 2mm. in diameter. They contain minute flecks of ore and probably represent unmixd titaniferous magnetite crystals, the ilmenite of which has been replaced by sphene, thus leaving a residuum of magnetite.

Apatite is present in accessory proportions.

Pyrite is present in small quantities. Subidioblastic crystals attain diameters of 0.1mm.

C. THE SPATIAL DISTRIBUTION OF PETROLOGICAL VARIATION IN THE SECOND-PERIOD DYKES

The First and Third-Period dykes are not numerous and have a restricted areal distribution; spatial analysis is therefore concentrated upon the dykes of the Second-Period suite.

1. The Spatial Distribution of Igneous Fabric Variations

In the Creag Mheall Beag area the northernmost dykes display marked internal heterogeneity and both sub-horizontal and sub-vertical mineralogical banding is developed. Towards the south of this domain heterogeneities within the dykes are less pronounced and mineralogical banding, where developed, is parallel to the dyke margins.

The widest dykes of the Poolewe area also illustrate considerable internal heterogeneity and banding of mineralogical constituents which is also parallel to the margins.

The dykes of the Kernsary and Beinn Airigh Charr areas are internally heterogeneous, but not to the same extent as in the Creag Mheall Beag and Poolewe areas; heterogeneities resulting from segregation of mineralogical constituents are elongate parallel to dyke margins.

It was argued in section IV.2 that the internal heterogeneities observed within the dykes represent relict igneous structures, and that the dykes having the greatest internal heterogeneities had differentiated within the least active tectonic environments. It follows that there are two possible explanations for the observed igneous petrological variations:-

(i) All the dykes were intruded into a tectonically inactive environment and the relatively homogeneous dykes of the Kernsary and Beinn Airigh Charr areas represent dyke domains in which there was a comparatively high rate of magma flow.

(ii) The internally heterogeneous dykes of the Creag Mheall Beag and Poolewe areas were intruded into less active tectonic environments than the dykes of the Kernsary and Beinn Airigh Charr areas.

The actual operative mechanism may involve a combination of both processes. Relatively short periods of tectonism, apparently not registered in the acid gneiss complex, may be separated by periods of quiescence. If the dykes, emplaced in periods of quiescence differentiated in situ, the likely consequence of the subsequent deformation of a partially consolidated dyke would be increased magma flow, possibly accompanied by the emplacement of new dykes at higher structural levels. According to such a hypothesis the dykes of the

Creag Mheall Beag and Poolewe areas represent samples from structurally deeper levels than the dykes of the Kernsary and Beinn Airigh Charr areas.

2. The Spatial Distribution of Metamorphic Fabric Variations

The Second-Period dykes of the Creag Mheall Beag area have schistose selvages, but most dykes are essentially epidiorites. The dykes of the Poolewe area are usually hornblende schists throughout, but in some of the relatively wide dykes near Naust, lenticular domains of epidiorite, several metres in diameter, are preserved between domains of hornblende schist.

In the Kernsary and Beinn Airigh Charr areas, most dykes are foliated throughout, but the foliation is not usually as finely developed as in the Poolewe area.

This distribution may be explained by variation in intensity of the D₆ deformation. In the Poolewe area, therefore, D₆ appears to be increasingly penetrative in a south-easterly direction, whilst in the other three areas D₆ is increasingly penetrative in a south-westerly direction from the Creag Mheall Beag area.

It was not possible to detect any variation in the metamorphic grade of M₆ between any of the areas studied. M₆ assemblages involving andesine, hornblende, garnet, biotite, quartz and sphene, are consistent with metamorphism in the amphibolite facies.

S₇ fabric development is restricted to the Beinn Airigh Charr and Poolewe areas; the diagnostic feature of the S₇ fabric within the dykes is the replacement of M₆ garnets by epidote and the increased proportion of epidote in the mode. In the Beinn Airigh Charr area S₇ becomes more penetrative towards the outcrop of the metasediments; within the Poolewe area, D₇ structures and the effects of M₇ are increasingly apparent in a south-easterly direction. Metamorphism

occurred in low amphibolite or upper greenschist facies.

The S8 fabric is a mylonitic banding usually associated with domains of F8 folding. In the Kernsary area a north-south-trending belt of steeply-dipping foliation to the north of Kernsary farm forms one limb of an F8 monoclinial structure (see Map 4); within this belt the dykes possess penetrative S8 foliation.

In the Beinn Airigh Charr and Poolewe areas, F8 folds are common but large scale F8 structures are less clearly defined than in the Kernsary area. The distribution of S8 is correspondingly inhomogeneous.

D. GEOCHEMISTRY OF THE DYKES

1. Introduction

Major element analyses were undertaken for:-

- (i) 4 samples of the First-Period dykes
- (ii) 19 samples of the Second-Period dykes
- (iii) 6 samples of the Third-Period dykes

Selected trace element analyses were made for:-

- (i) 3 of the 4 samples of the First-Period dykes
- (ii) all 19 samples of the Second-Period dykes
- (iii) 5 of the 6 samples of the Third-Period dykes

Selection of specimens for analysis was directed towards the study of several possible sources of geochemical variation viz:-

- (i) variation between the three dyke suites distinguished on a petrological and chronological basis,
- (ii) variation within a particular member and between the various members of the same suite,
- (iii) patterns of spatial variation between members of the same suite.

Such aims may appear ambitious in view of the small number of

analyses made; however, it was considered necessary to acknowledge all these possible sources of variation and hope that the present limited survey might reveal broad trends which could indicate the lines along which more detailed future research might be directed.

Since the Second-Period dykes are the most numerous and widely distributed, most of the specimens for analysis were selected from this group.

Tables IV.1 to IV.4 give the chemical analyses and various geochemical calculations for the dykes sampled. It is apparent that there is considerable variation between the samples analysed.

All of the dykes have been metamorphosed and are now amphibolites; the original igneous rock types and processes are therefore inferred by comparison of the chemical analyses with those of known igneous rock suites, a method successfully employed by Evans and Leake (1960). Implicit in this approach is the assumption that any variation between the analysed samples is the result of igneous processes, and not of any subsequent metamorphic readjustments.

Although cross-cutting relationships have led to the identification of three dyke suites, it has also been stated (section IV.A) that these suites cannot be distinguished tectonically. As an initial working hypothesis, it is assumed that the geochemical variation represented in the sampled dykes is the result of the differentiation of a single magma type.

2. Petrographical Characteristics and Affinities of the Dyke Suites

a. The First-Period Dykes

The mean composition of this group closely compares with the average of 28 tholeiitic olivine basalts given by Nockolds (1954) (see Table IV.4).

When plotted on the silica-alkali diagram (see Fig. IV.2) the First-Period dykes correspond with the tholeiitic basalts of Tilley (1950), but lie within the tholeiitic and high alumina basalt fields of Kuno (1968). Yoder and Tilley (1962) do not recognise high alumina basalt as an intermediate type between tholeiites and alkali basalts (Kuno 1960).

Hypersthene and olivine are important normative minerals in all the analyses of the First-Period dykes (Table IV.2b), which, according to the classification of Yoder and Tilley (1962) are therefore considered to be undersaturated tholeiites.

b. The Second-Period Dykes

Since there is considerable petrological variation within a single dyke for members of this group the mean chemical composition has been calculated for fine-grained marginal facies only, and the mean value so obtained compares closely with the average of 137 normal tholeiitic basalts, (Nockolds 1954) (see Table IV.4).

Silica-alkali plots for this suite (see Fig. IV.2) illustrate that the marginal facies have tholeiitic affinities, with dyke-centre facies extending into the alkali basalt field (Tilley 1950). By Kuno's (1968) classification the marginal facies of this group concentrate in the high alumina basalt field, whilst most derivatives plot in the alkali basalt field.

According to the scheme of Yoder and Tilley (1962) all of the analyses of the Second-Period dykes represent tholeiitic basalts; three analyses of dyke margins and twelve analyses of dyke centres represent oversaturated tholeiites; one analysis of a dyke margin and three of dyke centres correspond to undersaturated tholeiites.

c. The Third-Period Dykes

The mean chemical composition of this group (see Table IV.4)

resembles the normal tholeiitic basalt of Nockolds (1954). On the basis of the silica-alkali plots (see Fig. IV.2), the dykes of this suite have tholeiitic affinities (Tilley 1950), but cover the spectrum of alkali, tholeiite and high alumina basalts in the scheme of Kuno (1968).

By the classification of Yoder and Tilley (1962) all the dykes of this suite are tholeiitic basalt types; two analyses of dyke margins and one of a dyke centre correspond to oversaturated tholeiites; one analysis of a dyke margin and two analyses of dyke centres represent undersaturated tholeiites.

d. Geochemical Comparisons between the Dyke Suites

The AMF (cation) diagram (see Fig. IV.3a) illustrates a clear distinction in the distribution of the compositional fields of each dyke group. The First-Period dykes are relatively rich in magnesium, whilst the Second-Period dykes illustrate a relative iron enrichment, with subsequent differentiates demonstrating enrichment in alkalis. Dykes of the Third-Period occupy a compositional field which is intermediate between those of the First and Second-Period dykes.

The AMF (oxide) diagram (see Fig. IV.3b) enables comparisons to be made between the specimens analysed here and other well known analyses of differentiated tholeiitic suites, (Wager and Deer 1939, Walker and Poldervaart 1949). The plots of the three dyke suites together define a differentiation trend in which relative enrichment in iron or magnesium is important.

There is a broad overlap of the compositional fields of the three dyke groups when plotted on a $K^+ - Na^+ - Ca^{2+}$ diagram (see Fig. IV.3d); this diagram does, however, illustrate a general feature of the Second-Period dykes, in that most samples from dyke centres are richer in alkalis than samples of the margin facies.

Wager and Deer (1939) argued that the Skaergaard differentiation

trend towards iron enrichment, with later enrichment of alkalis and silica, was typical of average basaltic magma. Edwards (1942) and Walker and Poldervaart (1949) observed similar trends in the Tasmanian and Karroo dolerites respectively.

Osborn (1959) using the results of studies of the system $\text{MgO} - \text{FeO} - \text{Fe}_2\text{O}_3 - \text{SiO}_2$ (Maun and Osborn 1956) suggested that an olivine tholeiite magma would differentiate with iron enrichment if the oxygen content remained constant, which was dependent upon the magma having a low water content.

Fig. IV.4 illustrates how the samples analysed here correspond with Osborn's (1959) "tholeiitic trend". Thus if the three dyke groups are derivatives of a single magma type it seems likely that the emplaced magmas had a low water content.

The compositional fields of the Second and Third-Period dykes show greater overlap on the $\text{FeO} - \text{CaO} - \text{MgO}$ diagram (see Fig. IV.3c), compared with the AMF (cation) diagram (see Fig. IV.3a). Study of the $\text{FeO} - \text{MgO}$ axis is still most important in distinguishing the three dyke suites.

Fig. IV.4b illustrates a clear separation of the compositional fields of the three dyke groups. Increase in solidification index correlates with an increase in MgO ; the highest values were recorded for samples of the First-Period suite, and the lowest for samples of the Second-Period suite. All differentiated basalts have trends similar to that demonstrated in Fig. IV.4b (Kuno 1968).

Watterson (1968a) has distinguished two types of fractional crystallisation differentiation, namely "series differentiation" and "phase differentiation". The former is "due to separation and isolation of early formed minerals from the remaining liquid when the major phases crystallise together", whilst "phase differentiation is that

due to separation of different mineral phases" (Watterson op.cit.).

Watterson's (1968a) ideal differentiation trends are reproduced in Fig. IV.4c; the line AB represents ideal series differentiation, whilst the line CD represents ideal phase differentiation from an original parent magma having a composition represented by the point P.

Most of the analyses of margin facies plot near the point P, whilst the compositional fields of the three dyke groups are disposed in a manner which suggests that phase differentiation may provide an explanation of the variation between the dyke groups and within an individual group.

Watterson (op. cit.) explained the phase differentiation of the Ilordleq dykes as a response to crystallisation at high water-vapour pressure. However it is apparent from the AMF diagram (see Fig. IV.3b) that the sampled Lewisian dykes show a much greater variation in their MgO : FeO ratios than the Ilordleq dykes, and that the former show a greater affinity towards tholeiitic basalts which are considered to have differentiated under conditions of low water-vapour pressure.

A comparison of the norms of the three dyke groups (see Table IV.2b) reveals that it is mainly the variation in amounts of olivine which distinguishes them.

Fig. IV.3b illustrates the fractionation trend of Hawaiian olivine tholeiites and tholeiites; differences between end members of this trend have been explained mainly as a consequence of olivine settling (Macdonald 1944, Muir, Tilley and Scoon 1957).

Experimental work on tholeiites and olivine tholeiites has shown that "olivine is predominantly the first silicate phase to form" (Yoder and Tilley 1962). Green and Ringwood (1967) have demonstrated experimentally that, at atmospheric pressure, olivine is the first phase

to crystallise from an olivine tholeiite liquid, thereafter fractionation is governed by the precipitation of olivine and plagioclase together. However at pressures of 9kb. it was found that, of the basalts studied, olivine tholeiites had the highest olivine liquidus temperature and the largest temperature interval for the two phase assemblage of olivine and liquid; moreover it was also noted that at 9kb. plagioclase appeared late and in small quantities.

It seems unrealistic to envisage confining pressures as high as 9kb. for the dykes under discussion, but it is suggested that a relatively high confining pressure, in facilitating olivine fractionation from an olivine tholeiite liquid, could account for the trend of the plotted analyses (see Fig. IV.3b). It would also be possible to reconcile the phase differentiation hypothesis with differentiation under low water-vapour pressure.

Fig. IV.4d illustrates that the mafic index is important in distinguishing the three dyke groups, whilst the felsic index is important in distinguishing intra-group differences, especially in the case of the First-Period dykes. This pattern would be expected if the First-Period dykes represent accumulates of early-formed mafic phases. The Second-Period dykes illustrate a trend of increasing iron : magnesium ratio with increasing values of the felsic index - a predictable consequence of the fractionation of early-formed mafic phases (i.e. a "normal" differentiation trend).

3. Geochemical Variation within the Dyke Suites

a. Major Elements

Brief reference has been made (see section IV.D.2d) to some of the intra-group variation trends and it is apparent that they closely parallel many of the inter-group trends; this point is particularly

well illustrated by the plots of the analysed Second-Period dykes.

Two significant geochemical trends, one of iron enrichment, and another of slight enrichment in alkalis, are revealed; these are characteristic of middle and later stage differentiates of tholeiitic magmas. Other trends are illustrated in Fig. IV.5; the trends of the Karroo dolerites are inserted for comparison. It is apparent from these plots that the sampled First-Period dykes correspond to early differentiates of a tholeiitic magma, whilst some of the sampled Second-Period dykes of the Kernsary area correspond to the much later differentiates of tholeiitic magmas. Between these two extremes the majority of the samples, particularly those of the Second-Period dykes, define trends comparable with those of other tholeiitic suites and correspond generally with middle-stage fractionation products.

Of the plots illustrated (see Fig. IV.5a), three are worthy of more detailed consideration:-

(i) Niggli alk : mg. For the Second-Period dykes the trend has a negative slope and there is considerable variation in the mg and alk indices for any one dyke. Statistically dyke margins have higher mg indices and lower alk indices than the central facies of the dykes, although this pattern is reversed in the case of individual dykes.

For the First-Period dykes the alk indices appear to show little correlation with the mg indices.

The contrast between the poor correlation shown by the k : mg plot and the good correlation in the alk : mg plot may reflect extensive substitution between K^+ and Na^+ .

(ii) Niggli p : mg. The Second-Period dykes show the greatest diversity in their p indices. Wager (1963) on the basis of textural criteria has demonstrated concentration of phosphorus in the late stage differentiates of a tholeiitic magma. The negative slope

of the p : mg curve supports this conclusion, although within individual dykes there appears to be no simple pattern of variation. The relatively high phosphorus content of the Kernsary dykes is linked with a greater concentration of apatite in these dykes.

(iii) Niggli ti : mg. The Second-Period dykes display a trend which suggests enrichment of titanium in the middle and later stages of differentiation; the variation patterns within individual members of the suite are not, however, consistent. Comparison with other differentiated tholeiites (Wager 1960, Walker and Poldervaart 1949) leads to the conclusion that the titanium concentration is regulated by the crystallisation of titaniferous magnetite. The sampled Kernsary dykes are less isolated from the remainder of the Second-Period dyke plots on the ti : mg graph than on the p : mg and alk : mg plots, which suggests that crystallisation of titaniferous magnetite may have checked the trend towards iron and titanium enrichment before the latest stages of differentiation.

The sphene-magnetite intergrowths within the Second and Third-Period dykes may represent the metamorphic equivalents of titaniferous magnetite in the original igneous fabric.

Comparison of the plots of Fig. IV.5b with other tholeiitic series reinforces the suggestion that the First-Period dykes correspond with early stage differentiates, whilst the Kernsary dykes resemble later-stage differentiates.

Silica, alkalis, alumina and titanium are enriched in later differentiates whilst ferromagnesian constituents are concentrated in early tholeiitic derivatives.

Most of the plots of Fig. IV.5b show well defined trends both overall and for the Second-Period dykes. The variation patterns within individual dykes, however, reveal no consistent trends.

In the fm : si and al : si plots, the margin facies of the Second-Period dykes plot within the central portion of the trend line of the whole group; centre facies plotting away from this position probably represent mafic or felsic fractionation products.

b. Trace Elements

The concentrations of Sc, Cr, V, Sr, Ba, Cu, Ni, Zr and Co were determined by emission spectrographic techniques. Experimental error was defined simply as the difference between duplicate analyses. The standard deviation of the experimental error distribution for each element was determined. For the number of analyses made it is assumed that the error terms adopt a 't' distribution. Table IV.3a presents the mean values of duplicate analyses for the trace elements studied; Table IV.3b gives the standard deviation and three confidence limits for the respective error terms. Thus for each element it is possible to ascertain whether the recorded differences in trace element content between the analysed samples reflects real compositional differences, or are apparent and due to experimental errors.

Cr, Ba and Ni show considerable real variation with respect to the computed experimental error. Statistically significant concentration variations were revealed by Sc, V, Sr, Co, Zr and Cu but no inter-group, intra-group or geographically controlled variation trends were recognised, except in the case of Zr which showed appreciable concentration in the Kernsary dykes. Nockolds and Mitchell (1948) state that "Zirconium does not appear to enter any of the major minerals in appreciable amount, but is in the accessory mineral zircon". The appearance of zircon is associated with the later stages of crystallisation of basic magmas (c.f. Wager and Mitchell 1951), and is further evidence in favour of the Kernsary dykes being relatively late stage differentiation products.

Since magnesium is concentrated in early differentiates, whilst titanium is concentrated in the later differentiates of tholeiitic magmas, Cr, Ba and Ni are plotted against mg and ti (see Fig. IV.6). Similar plots have been used by Leake (1964) and Power and Park (1969). From these plots it is apparent that:-

(i) Barium exhibits no obvious variation trend although the centre facies of dykes are noticeably enriched when compared with margin facies; this feature is apparent both within individual dykes and for the Second-Period suite as a whole. Comparison of the Ba : mg plots with the k : mg plots (see Fig. IV.5a) reveals a close correlation between the two distribution patterns and reflects the strong geochemical coherence between barium and potassium.

(ii) Chromium is concentrated in the First-Period dykes and is present in smallest quantities in the sampled Kernsary dykes. The Third-Period dykes occupy an intermediate position between the fields of the First and Second-Period dykes. Wager and Mitchell (1951) note that chromium is concentrated in the early rocks of the Skaergaard intrusion; they quote a chromium content of 170 p.p.m. for the original magma, a figure very similar to the mean Cr value for marginal facies of the Second-Period dykes. Concentrations of 1500 p.p.m. of chromium were attained in some of the Skaergaard gabbro picrites by accumulation of early formed chrome spinels, whilst olivine was a commonly associated cumulus phase. Walker and Foldervaart (1949) also record the early separation of picotite and olivine in the Elephant's Head picrites.

The chromium distribution trends in the Skaergaard and Karroo series are so similar to those of the present study that it seems likely that the fractionation of chrome spinels may have played an important part in concentrating chromium in the First-Period dykes. Another consideration which may have relevance to the fractionation of chromium

is the fact that chromium enters abundantly into early formed pyroxene (Wager and Mitchell 1951).

(iii) Nickel is also concentrated in the First-Period dykes, whereas the lowest nickel concentrations were recorded for the Kernsary dykes.

Vogt (1923) demonstrated that nickel in igneous rocks was concentrated in magnesium silicates and that there was a sympathetic variation between nickel and magnesium concentrations; he also showed that olivine was the silicate phase in which nickel was most concentrated. Wager and Mitchell (1951) observed agreement with Vogt's conclusions for the Skaergaard rocks whilst Walker and Poldervaart (1949) have demonstrated that nickel is associated with the earliest crystal phases.

Thus the evidence from the trace element concentrations strengthens the argument that the First-Period dykes represent picritic cumulates, whilst the sampled Kernsary dykes represent later stage differentiation products of tholeiitic magmas.

4. Spatial Patterns of Geochemical Variation

Consideration is restricted to dykes of the Second-Period suite, since they have the broadest areal distribution and have been most intensively sampled within the area studied.

The major and trace element analyses indicate a geographical distribution of chemical variation such that the dykes of the Kernsary area correspond with relatively late stage differentiates of a tholeiitic magma, whilst the Second-Period dykes of the Creag Mheall Beag and Poolewe areas correspond with the middle stage differentiation products.

Many of the dykes of the Kernsary area contain microcline which has been metasomatically introduced (see section IV.B.2d(iv)), and it was therefore considered that the chemical individuality of the Kernsary dykes may be the result of metasomatic processes. This suggestion has,

however, been rejected since only one of the chemically analysed dykes contained microcline. Consideration of elements other than potassium also establishes the Kernsary dykes as relatively late stage tholeiitic differentiates, since it is extremely unlikely that metasomatism could have adjusted all these elements to simulate magmatic differentiates.

Graphs plotted with $\text{Fe}^{2+} : \text{Fe}^{3+}$ as ordinate have revealed no consistent trend; however, it is apparent that for the Second-Period dykes of the Poolewe area the oxidation ratios cluster about a value of 3.5 and appear to be significantly different to the corresponding values for the Creag Mheall Beag and Kernsary areas which cluster about a value of 2.6. Such differences are probably accountable in terms of post-dyke deformational and metamorphic events.

5. Summary of the Geochemical Data

The geochemical data as a whole lead to the following conclusions:-

(i) The dykes of the First-Period suite are chemically equivalent to picrites and represent the accumulates of early formed phases of tholeiitic magmas. The separation of early formed olivines from the magma provides the most likely mechanism to explain the geochemical data, although pyroxene and chrome-spinel fractionation may also have been effective.

(ii) The Second-Period dykes are chemically equivalent to dolerites and gabbros and compare closely with the middle and later stage fractionation products of tholeiitic magmas; the sampled Kernsary dykes appear to represent the later stage differentiates. Decreasing magnesium ratios in the later stages of differentiation may have been effected by the early fractionation of olivine, but the occasional appearance of olivine in the normative mineralogy of this group leads to the suggestion that pyroxene fractionation may have been a more effective

mechanism.

Iron and titanium enrichment trends in the later differentiation stages were probably controlled by the crystallisation of titaniferous magnetite. Increasing alkali and silica contents and decreasing mafic indices in the later differentiates are likely consequences of increased feldspar and quartz in the rock mode.

(iii) The Third-Period dykes form a group chemically intermediate between the two earlier dyke generations.

6. Some Comparisons with Other Scourie Dykes

Table IV.4 illustrates average compositions of dolerite dykes in the Scourie-Loch Laxford area of Sutherland (Burns 1966). These analyses closely resemble the mean value of analysed Second-Period dyke margins (see Table IV.4) although the Sutherland dykes are richer in TiO_2 and CaO and correspondingly poorer in MgO and Al_2O_3 .

Comparison of the plots of analyses of the Second-Period dykes with those of other analyses from the Southern Region of the mainland Lewisian outcrop reveals similar geochemical fields and trends (Park 1966, Cresswell 1969).

It is also apparent (see Table IV.4) that the Torridon type TB and TD basites (Cresswell 1969) are geochemically similar to the First and Second-Period dykes respectively; these similarities also express themselves petrologically. However, in the Torridon area the type TB basites were emplaced after the type TD basites. Such apparently contradictory evidence need not involve any conflict of opinion in view of the complexity of the intrusion sequence established by Tarney (1963) in the Assynt area of the Central Region of the mainland Lewisian outcrop. Indeed, it is commonly found in suites of igneous rocks that the order of emplacement does not necessarily correspond with the position in the supposed differentiation sequence,

although it is likely that rocks formed by in-situ accumulation of crystals, or by filter pressing, will be post-dated by rocks formed from their respective residual fractions (Watterson 1968).

Cresswell (1969) suggests that the primary crystallisation and fractionation of amphibole may have been an important differentiation mechanism in the Torridon type TB basites. However, although Tarney (1963) records kaersutite in the olivine gabbro dykes of the Assynt area, primary amphibole does not appear to be abundant in any of the Assynt dykes; it is therefore unlikely that amphibole fractionation has been important in differentiation there.

In contrast, olivine and possibly pyroxene fractionation have been proposed as likely differentiation mechanisms (see sections IV.B2b and IV.D3); important in this respect are the cross-cutting picrite and layered gabbro intrusions occurring to the south-west of the Gruinard River (Bowes, Wright and Park 1964). The layering of these bodies comprises primary precipitate olivine and pyroxene crystals and interprecipitate labradorite; Park (1970 p.395) states that "Clearly these bodies are broadly correlatable with the Scourie dyke swarm". This and the evidence from the comparatively unmodified dykes of the Central Region (Tarney op. cit.) lends support to the olivine fractionation mechanisms proposed here and also corroborates O'Hara's statement (1968 p.96) that "Quartz-normative tholeiites have probably attained their present compositions by continuous olivine fractionation unaccompanied by extensive fractionation of other phases".

It is possible, however, that magmatic differentiation of the dyke suites may have been controlled by olivine fractionation, but for the dykes themselves to have crystallised as primary amphibolites. Windley (1970) cites examples from Greenland in which relatively dry tholeiitic magma crystallised as primary amphibolite upon emplacement

into a metamorphic environment.

O'Hara (1961) and Tarney (1963) have argued that the Scourie dykes were intruded into hot country rock. The occurrence of chlorite in the First-Period dykes may be cited as evidence in support of such a conclusion. This chlorite is similar in its mode of occurrence and optical properties to that observed in the Gruinard and Gleann Tulacha metasediment groups, the Beinn Airigh Charr basite, and also in the kyanite gneisses and "tremolite rock". In all these rocks the chlorite was considered to be a static M5 phase.

Within the dykes, chlorite and relict igneous plagioclase crystals comprise the oldest fabric elements, and have been replaced or modified by S6 fabric elements. It is therefore possible to argue either that all chlorite crystallisation occurred subsequent to the emplacement of the First-Period dykes, or that the static M5 crystallisation of chlorite continued into the period of dyke emplacement. Both of these alternatives imply dyke emplacement into a metamorphic environment.

Tarney (1963) considered that the absence of a reaction relationship between olivine and orthopyroxene in the Assynt picrites and the unserpentinised nature of the olivine in equivalent thoroughly altered picrites, indicated dyke emplacement at pressures corresponding to depths between 15 and 20km. of the earth's crust, and country rock temperatures of 500°C.

Within the pressure regime envisaged by Tarney (1963) the Mg-rich chlorite + kyanite + quartz assemblage would be stable up to about 600°C, whilst at temperatures of 500°C this assemblage would be unstable at pressures below 4kb. (Seifert and Schreyer 1970).

Other evidence which may be taken as indicative of dyke intrusion into a metamorphic environment is the nature of the relict

igneous fabric of the Third-Period dykes, which is finer grained and texturally more homogeneous compared with adjacent Second-Period dykes of similar width. If the First-Period dykes were emplaced into hot country rocks, it may be argued that succeeding phases of injection occurred into a progressively cooler complex.

Conclusions which may be drawn from this comparative analysis are that the First-Period dykes may represent intrusion into the hottest country rock where cooling of the emplaced magma was slow, facilitating differentiation and allowing the emplacement of magma into higher structural levels than the present level of exposure. The First-Period dykes could thus represent crystal cumulates at low structural levels.

The Second-Period dykes may represent intrusion into a cooler complex, the present level of exposure representing comparatively higher levels in the emplacement sequence with corresponding middle and late-stage magmatic differentiation products. The complex would, however, still be hot enough to cause very slow cooling, enabling the segregation of mafic and felsic minerals to take place under favourable circumstances (see section IV.B2a).

Intrusion of the Third-Period dykes may have occurred into a comparatively cool complex, perhaps so cool that strong magmatic differentiation was inhibited, thus accounting for the geochemically intermediate character of the Third-Period dykes between those of the First and Second-Period suites.

The dyke emplacement scheme outlined above thus envisages the three dyke suites as derivatives from a common source area.

CHAPTER V

THE POST-DYKE DEVELOPMENT OF THE COMPLEX

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1. The S6 Fabric

2. The S7 and S8 Fabrics

B. THE GLEANN TULACHA METASEDIMENTIS

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a. The S6 Fabric

b. The S7 and S8 Fabrics

2. Quartzites

3. Mica Schists

a. The S6 Fabric

b. The S7 and S8 Fabrics

C. THE GRUINARD BASITE AND METASEDIMENTIS

1. The S6 Fabric

2. The S7 and S8 Fabrics

D. THE ACID GNEISS COMPLEX

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b. The S6 Fabric Modifications of Earlier Fabrics

- (i) Acid Gneisses
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4. Acid Veins

5. The Development of Late-Stage Alkali Feldspar

- a. Mineralogical Features
- b. Petrological Features
- c. The Distribution of K-feldspar within the Gneiss Complex
- d. The Source of the Alkali Feldspar
- e. The Argument for K Metasomatism
- f. The Age of the K Metasomatism

E. THE POST-DYKE METAMORPHIC EVENTS

1. The M6 Metamorphism

2. The M7 and M8 Events

3. Post-Dyke Fabric Evolution

CHAPTER V

THE POST-DYKE DEVELOPMENT OF THE COMPLEX

In Chapter III the important part played by compositional, structural and metamorphic anisotropies in the evolution of the pre-dyke complex is explained. A similar theme is expressed in this Chapter; presentation is likewise organised on the basis of fabric criteria.

Each fabric end member shows variation in development, both with respect to the major lithological units mapped, and within these units. Such development is an important factor in analysis, since it enables comparative studies to be made of different materials undergoing deformation and metamorphism, whilst it is the preservation of relics of earlier fabrics and mineral assemblages which provides the means to elucidation of the long and complex deformational and metamorphic history of these Lewisian rocks.

Three post-dyke deformational episodes have been recognised in the complex; these are labelled D6, D7 and D8 and are associated with S6, S7 and S8 metamorphic fabrics respectively. In addition a late deformational episode, which resulted in the production of cataclasites and mylonites with associated pseudotachylite, has been termed D9. S9 is therefore a mylonitic banding located within prominent crush zones indicated on Maps 3-6.

A. THE BEINN AIRIGH CHARR BASITE

1. The S6 Fabric

Quartz forms xenoblastic grains which demonstrate pronounced elongation parallel to transposed S5. The mean length of crystals in sections cut perpendicular to I6 is 0.2mm. and the mean breadth : length

ratio is 0.3. Grain boundaries are usually irregular and sutured. Strain shadows and Boehm lamellae are commonly developed.

Plagioclase (An 28%) occurs as xenoblastic, inequant grains. Crystal margins are irregular. The mean grain size is 0.2mm. Accurate determinations of An content were not made due to the small size and turbid nature of many of the grains. Fresh crystals exhibit both albite and pericline twins with marked, often complex, patterns of compositional zonation.

Hornblende usually forms relatively large subidioblastic crystals. In the basites which are dominantly composed of quartz, plagioclase and hornblende, basal sections of M6 hornblende crystals have a mean diameter of 0.3mm., and the size contrast with the M5 hornblende is immediately apparent (see Plate V.1a). The planar orientation of the M6 hornblende forms a marked contrast with the strong linear orientation of the M5 hornblende.

In the basite samples containing more than 15% of chlorite or biotite, the M6 hornblende occurs as large subidioblastic crystals; diameters of basal sections attain 4mm.; prismatic sections exceed 1cm. in length.

The pleochroic scheme is X - pale greenish yellow, Y - green, Z - deep blue green with $Z > Y > X$. Absorption and pleochroism of this and most of the M5 hornblende is such as to suggest that the hornblende is a pargasitic variety.

The relatively coarse-textured basite samples provide most of the evidence of mineral paragenesis, for example in Plate V.1b, M6 hornblende has clearly replaced chlorite and magnetite trails which are contained in the chlorite {001} cleavage traces are incorporated within the hornblende as an internal S5 subfabric.

M6 hornblende growth began, in a few instances, with

intergrowths of acicular crystals displaying marked discordance with S5; most crystals, however, occur as discrete individuals in planar orientation; this preferred planar orientation preference is considered to represent mimetic overgrowth parallel to a pre-existing S-surface and that M6 hornblende growth occurred during a static phase of metamorphism.

However, near the marble-basite contact, in a structure which appears to represent one limb of a large-scale F6 fold, the M6 hornblende crystals contain sigmoidal inclusion trails (see Plate V.2a). The trails are continuous with the external foliation and the hornblende is thus considered to be syn-tectonic. The association of M6 syn-tectonic hornblende with areas in which the rocks display marked contrasts in competency is regarded as evidence of protracted strain in these areas, so that deformation continued into what was elsewhere a static metamorphic phase.

Biotite forms decussate aggregates of subidioblastic crystals. These show specific concentration in the hinge zones of chevron F6 folds (the most common mesoscopically identified folds within the Beinn Airigh Charr basite). Crystals have a mean length of 0.5mm. measured parallel to the {001} cleavage, although some crystals exceed 1mm. in this direction.

On F6 fold limbs biotite shows a strongly-developed preferred orientation, most of the crystals having slender form.

Pleochroism with absorption is according to the scheme
X - pale yellow, Y - brown, Z - lustrous red brown with $Z > Y > X$.

It is concluded that biotite grew as a static M6 phase, producing decussate aggregates along F6 chevron fold hinge zones, and also in biotite-rich basite samples; mimetic biotite growth, parallel to S5, is however characteristic on the limbs of F6 folds.

2. The S7 and S8 Fabrics

The S7 and S8 fabrics cannot satisfactorily be distinguished microscopically. The existence of S7 and S8 events may be proved using field evidence of interfering fold sets. Distinct S7 and S8 surfaces were not commonly produced, although a few examples of segregation banding were observed on the limbs of asymmetric F7 and F8 folds (see Plate V.2b).

The dominant S7 and S8 fabric elements are strain modifications of older fabrics; neocrystallisation is not a pronounced feature.

Quartz shows well developed strain effects and the production of a mylonitic subfabric (see Plate V.3).

Chlorite and Biotite of M5 and M6 generation show the effects of interlayer slip, pronounced kinking and ultimate granulation.

Epidote was not commonly observed in the Beinn Airigh Charr basite, but tends to be concentrated in restricted domains, within which it sometimes exceeds 15% of the mode. Both idioblastic crystals and subidioblastic equidimensional granules were observed. The mean grain size is 0.1mm. Crystal margins are smooth or slightly irregular. Most epidote replaces hornblende. If biotite is also present it usually displays partial replacement by penninite.

The localised occurrence of epidote within the Beinn Airigh Charr basite leads to the conclusion that proximity to the acid gneisses has been an important control over the formation of epidote.

Sphene and Anatite are present in accessory proportions.

Iron ores of various types are observed in rock sections possessing S7 and S8 fabrics, but none of these ores is considered to be of M7 or M8 paragenesis.

Magnetite and Ilmenite intergrowths crystallised in M5 and M6.

Pyrite forms idioblastic cubes, subidioblastic aggregates and

thin sheet-like bodies which have not been affected by F7 or F8. There is considerable variation in the size of individual crystals; the mean diameter of subidioblastic forms is 0.2mm.

Hematite occurs as irregular aggregates or thin coronas around pyrite, which it is therefore considered to post-date.

B. THE GLEANN TULACHA METASEDIMENTS

1. Calcareous Rocks

These have an abundance of microfold sets which has enabled a fabric sequence to be elucidated. In most cases, fabric analysis does not permit distinction between S7 and S8 fabrics, for example Plate III.5a illustrates a case in which it is not possible to assign the refolding of the muscovite flake to F7 or F8.

a. The S6 Fabric

Calcite forms an equigranular granoblastic mosaic in the pure marbles. The mean grain diameter is 0.7mm. Most crystals are subidioblastic and grain boundaries are slightly curved, rarely smooth, but not markedly irregular. Glide twinning is commonly developed.

In the more impure marbles and calcareous schists, calcite shows greater variability in grain size. Irregular xenoblastic crystals exceeding 0.25mm. in diameter are set in an equidimensional granular matrix in which the mean crystal diameter is 0.05mm.

The calc-silicate schists contain markedly xenoblastic calcite forms. There is great variation in grain size and shape. The largest crystals are elongate parallel to L6 and may exceed 4mm. in this direction. Average breadth : length ratios for such large crystals are 0.3 for sections cut perpendicular to the foliation. Smaller crystals are more equidimensional. Most crystals have extremely irregular margins. Glide twinning is commonly developed.

Dolomite occurs in the more impure marbles and calcareous schists. It forms equigranular subidioblastic granules having a mean grain size of 0.05mm. and is invariably associated with calcite.

Garnet has restricted occurrence and was observed in the calcareous schists. It is idioblastic and colourless and overgrows F6 folds of the lithological layering. Crystal diameters in excess of 1.4mm. were recorded. Crystal boundaries are smooth, straight or slightly curved. Inclusions are not common. Growth probably occurred in static metamorphic conditions.

Phlogopite was observed in some of the dolomitic marble horizons. Most crystals occur as discrete xenoblasts in sub-parallel alignment. Both stout and slender forms are developed. The mean diameter of basal sections is 0.2mm. Boundary surfaces are smooth and straight parallel to $\{001\}$ but uneven in other directions. Pleochroism with absorption is weak, X - colourless, Z - pale buff.

Tremolite forms more than 50% of the mode of some specimens and is the dominant calo-silicate mineral. It forms sheaf-like aggregates of acicular crystals or large xenoblastic grains. The largest crystals attain diameters of 1.5mm. and contain internal S5 subfabrics of quartz and magnetite inclusions. Crystal boundaries are usually irregular.

Quartz in small quantities forms the usual impurity of the impure marbles, but may constitute more than 15% of the mode in the chemically less differentiated calcareous metasediments. The quartz subfabric is granoblastic; grains are not markedly inequant, but define S6 by their dimensional orientation preference. The mean grain size is 0.1mm. Crystal margins are irregular but not strongly sutured. Most crystals are strained.

Plagioclase (An 26%) usually occurs as fresh xenoblastic

crystals in a granoblastic subfabric. The mean grain size is 0.15mm., but some crystals exceed 0.25mm. in diameter. Crystal margins are irregular, and a stepped appearance is produced where albite twin lamellae make a large angle with the crystal margin. Some crystals display zonation, usually normal, but sometimes reverse and then normal; a few individuals show two oscillations. The maximum compositional variation in any one crystal is usually less than 5% An content.

Microcline is present as isolated crystals in some of the quartzo-feldspathic domains of the calc-silicate schists. Most crystals are xenoblastic and rarely attain 0.2mm. in diameter.

b. The S7 and S8 Fabrics

D7 and D8 episodes produced noticeable strain effects in phases of M5 and M6 generation. Mica and chlorite were particularly susceptible and usually show evidence of folding on a microscopic scale. Recrystallisation effects are most pronounced in the quartz and calcite subfabrics.

Quartz displays xenoblastic forms as a result of polygonisation and recrystallisation. Recrystallisation in association with F7 and F8 folding produces axial planar foliation described by the quartz subfabric (see Plate V.4).

Calcite recrystallisation has produced small calcite granules around the edges of pre-M7 calcite crystals. Some glide twinning was probably accomplished in D7 and D8.

Zoisite occurs as idioblastic crystals which have replaced muscovite and biotite intergrowths.

Tourmaline Sub-idioblastic crystals attain diameters of 0.2mm. Most crystals display zonation. The relative age is uncertain.

Iron Ore in the calcareous rocks is most common in the calc-silicate schists.

Magnetite occurring as xenoblastic grains forms elongate crystals parallel to S5. Most crystals are less than 0.1mm. in their greatest dimension; many now form inclusions in tremolite of M6 age.

Pyrite has subidioblastic form and clearly overgrows the S6 fabric. The largest cubes occur in the calc-silicate schists and in these rocks the mean grain size is 0.1mm.

Hematite occurs as irregular masses. It is usually subordinate to pyrite, about which it frequently forms a thin corona.

2. Quartzites

Each of the post-dyke deformational events, D6, D7 and D8, produced a quartz subfabric. In the purer quartzites it is difficult to designate a particular fabric in the absence of mesoscopically identifiable folds. For the more impure quartzites, however, it is possible to establish a fabric sequence by microscopic analysis.

Post-S5 fabrics have been distinguished from S5 fabrics where the post-S5 foliation has developed obliquely to the S5 compositional layering, or where M5 quartz grain-size contrasts have been only partially obscured by the effects of post-M5 metamorphism (see Plate V.5a).

Relationships between porphyroblasts and matrix are also useful in determining the relative age of fabrics developed; for example in Plate III.4a the internal S5 fabric of the porphyroblast is now oblique to the dominant S6 external foliation.

Relatively large muscovite crystals have also provided a basis of fabric identification; such crystals sometimes attain lengths of 0.7mm. and are usually discordant to planar fabric elements. Some of

the muscovite crystals have been deformed, others have not; since all the discordant muscovite is considered to be paragenetic, the fabrics in which such muscovite is deformed post-date those in which it is undeformed.

Quartz recrystallisation in each of the post-dyke metamorphic episodes involved the progressive destruction of the S5 granoblastic fabrics. The resultant fabrics display marked inequigranularity; grains are extremely strained and possess strongly sutured margins. Typical breadth : length ratios are in the range 0.4 to 0.3. Greatest elongation occurs parallel to the foliation and the mean length in this direction is 0.3mm.

Feldspar of several types was observed in quartzites containing undeformed discordant muscovite. Plagioclase (An 26%) is fresh and occurs as equigranular xenoblastic grains; the mean diameter is 0.3mm. Grain boundaries are irregular and show evidence of reaction with quartz. Some oligoclase crystals possess irregular, discontinuous rims of alkali feldspar. Other feldspars illustrating similar paragenetic relationships are classified as string antiperthites, (Andersen 1928). Feldspar usually constitutes less than 3% of the mode in the quartzites.

Biotite was observed in some of the more impure quartzites. It forms xenoblastic flakes and scaly aggregates. The mean diameter of basal sections is 0.1mm. Both stout and slender forms are developed. S-surfaces defined by the preferred orientation of biotite pre-date the formation of discordant muscovite crystals. Pleochroism with absorption is strong, X - pale yellow, Z - lustrous red brown. Pleochroic haloes are common.

Iron Ore occurs as irregular grains, sometimes exceeding 0.5mm. in their greatest dimension. Hematite is dominant, but

sometimes preserves a core of magnetite. Grain concentrations are dominantly parallel to S5.

3. Mica Schists

a. The S6 Fabric

D6 involved widespread transposition of S5 in the mica schists, and a new metamorphic fabric was imparted.

Quartz occurs as xenoblastic grains which show elongation parallel to S6. The mean length of crystals in sections cut perpendicular to L6 is 0.2mm. and the breadth : length ratio is in the range 0.3 to 0.4. Most crystals are strained. Grain boundaries are straight, slightly curved or irregular. Forms commonly display marked angularity and strongly sutured crystal margins are abundant.

Plagioclase (An 24%) Fresh, xenoblastic, inequant crystals display both albite and pericline twinning. The mean grain diameter is 0.15mm. Crystal margins are irregular and stepped. Some crystals show normal zonation and have a core composition of An 26% grading to An 22% at the margin.

Biotite usually forms discrete xenoblastic crystals which define S6. The mean diameter of basal sections is 0.1mm. although the largest flakes exceed 0.3mm. in diameter. Crystal margins are well formed and straight parallel to $\{001\}$ but ragged in other directions. Pleochroism is X - pale yellow, Z - red brown. Pleochroic haloes are common. Biotite replaces M5 static chlorite, usually by means of homoaxial overgrowth; such a process results in extremely slender biotite forms parallel to the chlorite $\{001\}$ cleavage traces, and stout lenticular forms where biotite replacement has not extended itself very far along the chlorite basal cleavage.

Tremolite forms sheaf-like aggregates and subidioblastic

prismatic crystals showing greatest elongation parallel to S6, but with no preferred linear orientation. Individual crystals attain diameters of 0.4mm. in basal section and lengths of 1mm. in prismatic section. Sheafs of acicular intergrowths exceed 4mm. in their greatest dimension. Most tremolite is associated with the relatively mafic domains. Trails of quartz and magnetite inclusions define an internal S5 fabric. Crystal margins are irregular and many crystals are discordant to, and replace, M5 chlorite. Sometimes tremolite extends along the chlorite {001} cleavage traces.

$$Z^{\wedge}C = 16^{\circ}, \quad 2V = 80^{\circ} \text{ with negative orientation.}$$

b. The S7 and S8 Fabrics

These cannot satisfactorily be distinguished microscopically. A mylonitic quartz subfabric was produced and pre-M7 phases were deformed. Mica schists possessing S7 and S8 fabrics typically have mesoscopically penetrative microfold sets. The wave-length of such folding may be 0.3mm. or less.

Quartz has been recrystallised to produce xenoblastic grains which have strongly sutured margins and undulose extinction. Most crystals are inequant; typical breadth : length ratios average 0.3.

Phyllosilicates which formed prior to M7 were deformed in D7 and D8. The most common structure produced was kink banding on a crystallographic scale. No appreciable recrystallisation occurred in M7 or M8.

Apatite and Tourmaline constitute a very small proportion of the rock mode. Forms are idioblastic and subidioblastic. Crystal dimensions rarely exceed 0.1mm. Their chronological position in the metamorphic sequence remains obscure.

Magnetite occurs in small granular concentrations and as trails parallel to S5, but now enclosed within M6 tremolite.

Pyrite has idioblastic and subidioblastic forms, some cube faces exceed 0.5mm. in length and have overgrown the S8 fabric. Many crystals have a thin corona of hematite.

Hematite occurs in thin sheets, usually less than 0.2mm. thick. These show general concordance with the S5 lithological layering; in detail they illustrate discordance with S8, which they are therefore concluded to post-date.

C. THE GRUINARD BASITE AND METASEDIMENTS

The Gruinard basite and metasediments are considered together, in view of their restricted outcrop and interdigitation. In most samples of the Gruinard metasediments it is difficult to distinguish the S5 and S6 fabrics. However, the presence of M5 chlorite in some of the garnetiferous hornblende schists of the basite enables this distinction to be made. The chlorite subfabric described in section III.B.2a is considered to be equivalent to similar static metamorphic subfabrics described in the acid gneiss complex (sections III.A1, V.D1b), the Beinn Airigh Charr basite (section III.C1) and the Gleann Tulacha metasediments (section III.B1a & d).

1. The S6 Fabric

S6 is not a well developed surface. M6 phases apparently grew in static metamorphic conditions.

Biotite has replaced chlorite (see Plate V.5b) and a decussate subfabric of discordant biotite flakes is therefore considered to post-date both chlorite crystallisation and the planar S5 biotite subfabric. Most crystals are subidioblastic and the mean diameter of basal sections is 0.8mm. Pleochroism with absorption is X - colourless, Z - pale brown.

Hornblende The M6 hornblende subfabric likewise comprises crystals discordant with S5. No linear M6 hornblende orientation is

apparent and the tendency towards a planar arrangement probably represents mimetic overgrowth of S5. Most hornblendes are subidioblastic and include fragments of plagioclase, quartz and magnetite crystals. There is considerable variation in grain size; prismatic sections sometimes exceed 1cm. in length. Pleochroism with absorption is according to the scheme X - pale green, Y - green, Z - bluish green with $Z > Y > X$.

Plagioclase (An 31%) occurs as xenoblastic polygonal grains. Mostly these are quite fresh. The mean grain size is 0.2mm. Crystal margins are smooth, straight or slightly curved, and tend to be more irregular adjacent to quartz rich domains. Many crystals display evidence of zonation, initially reverse, but succeeded by a normally zoned mantle; the maximum difference in composition between adjacent zones is An 5%.

Quartz forms xenoblastic crystals which usually have smooth and rounded margins. There is considerable variation in grain size, the mean value being 0.15mm. Some of the larger quartz crystals contain numerous bleb-like inclusions of biotite, hornblende and feldspar. Most quartz crystals show evidence of strain in the form of undulose extinction.

Garnet Static M6 garnets are idioblastic to subidioblastic and are filled with inclusions of which quartz and magnetite predominate. Individual crystals exceed 1cm. in diameter. Crystal margins are smooth and straight, but sometimes slightly irregular where the overgrown S5 fabric has been incompletely digested.

Apatite occurs in accessory proportions and forms subidioblastic crystals having a mean diameter of 0.1mm.

Pyrite forms idioblastic cubes; the length of cube faces sometimes exceed 2mm.

Hematite forms coronas around pyrite and is sometimes developed along biotite $\{001\}$ cleavage traces.

2. The S7 and S8 Fabrics

These have not been specifically recognised in the Gruinard basite and metasediment tract.

D. THE ACID GNEISS COMPLEX

The dominantly quartzo-feldspathic nature of the acid gneiss complex and the absence of mesoscopic F6 folds over much of the area has made it difficult to recognise the S6 fabric within these rocks. Evidence has been advanced in Ch. IV (see also Ch. VI) which illustrates that dyke intrusion was not a single event. There is, on the other hand, no evidence to show that any major structural or metamorphic events affected the gneiss complex as a whole during the period of dyke emplacement.

It is also apparent that the dykes in the Creag Mheall Beag area differ considerably from those studied further south (see section IV.C2). The dykes of that northern area commonly have schistose margins, but centres of all but the thinnest dykes are typically poorly foliated or completely unfoliated. In contrast, the southern dykes are characteristically well foliated and schistose throughout.

The dominant schistosity within the dykes of the Poolewe and Beinn Airigh Charr areas has been affected by two further deformational episodes, i.e. D7 and D8. These latter episodes have also been identified within the acid gneiss in these areas where both dykes and gneisses have been folded about common axes.

Comparison of the gneisses in the Creag Mheall Beag area with those further south reveals important fabric differences, not attributable to the effects of D7/M7 or D8/M8, nor indeed to any known

pre-dyke lithological contrasts, and which are therefore attributed to the effects of D6 in the gneisses of the southern area.

1. The S6 Fabric

S6 is most intensively and extensively developed on the moderately and steeply-dipping southern limb of the Carnmore antiform. To the south of the Loch Maree fault, S6 is not easily recognised in the acid gneisses; in the Creag Mheall Beag area S6 is associated with mesoscopic F6 folding not observed in the southern areas.

Wherever S6 is developed it is characterised by inhomogeneity, both in its distribution and its intensity of development (e.g. see Plate VI.11 which illustrates the development of S6 in narrow domains parallel to the thinned limbs of F6 folds in the Creag Mheall Beag area and also Plate V.6a).

Usually S6 in the acid gneisses is a modified pre-existing surface, so that relicts of pre-M6 phases are common. Plagioclase feldspar appears to be particularly refractory. However, specimens collected from localities adjacent to the large crush belts of the Creag Mheall Beag area, combined with evidence obtained in the Kernsary area, lead to the conclusion that completely new fabrics were produced during M6 within restricted domains.

a. The "new" S6 Fabric

Plate V.6b illustrates a typical example of this fabric.

Quartz forms irregular xenoblastic grains displaying slight elongation parallel to S6. The mean grain diameter is 0.3mm. although the largest crystals exceed 0.5mm. in this respect. Undulose extinction as a result of strain is characteristic. Crystal boundaries are smooth or slightly curved.

Plagioclase feldspar (An 25-27%) forms an equigranular

granoblastic mosaic of xenoblastic polygonal grains. Most are fresh, but turbidity results from subsequent retrogression. The mean grain diameter is 0.15mm. and the largest grains seldom exceed 0.25mm. Crystal boundaries are smooth and slightly curved; inclusions are rare. Most crystals show evidence of slight zonation, initially reversed and then normal, with gradational contacts between adjacent zones. Twinning is not commonly developed.

Biotite occurs as both stout and slender discrete, decussate, subidioblastic flakes. It sometimes forms homoaxial intergrowths with muscovite. The biotite subfabric appears to have replaced the granoblastic quartzo-feldspathic fabric. There is considerable variation in grain size, and the largest flakes exceed 1.5mm. in basal section diameter. Many crystals have been replaced by a pale yellowish green chlorite and lenticular prehnite crystals which have developed parallel to the biotite $\{001\}$ cleavage traces.

Magnetite forms irregular elongate subidioblastic crystals, usually less than 0.2mm. in length. Crystal margins present smooth and straight outlines towards other phases.

Epidote and Zoisite are present in accessory proportions.

b. The S6 Fabric Modifications of Earlier Fabrics

Plates V.6a and VI.11 demonstrate mesoscopically the differential development of the S6 fabric. Parallel effects are visible microscopically, and contrasting domains of relatively unmodified pre-S6 fabrics and S6 fabrics may be identified within the scale of a single thin section.

In order to investigate these differences simple measurements were made upon three thin sections, chosen such that the three main phases constituting the acid gneisses, viz. quartz, plagioclase feldspar and

biotite, were not obviously banded, clustered or otherwise segregated. The sections were cut perpendicular to the prominent mineral lineation and simple breadth : length ratios were measured for populations of each of the three phases. Domains of the selected thin sections were classified as "S6" or "pre-S6" and two traverses, in which the breadth : length ratio of each grain encountered was measured, were made for each domain recognised. The results are illustrated in Table V.1 (see also Plate V.7a).

It is apparent in Table V.1 that there is a significant contrast in grain shapes between the S6 and pre-S6 fabrics; the former is characterised by an increased tendency towards inequant grain forms, particularly in the case of quartz. Minerals such as biotite, which normally have a platy habit, show little modification of their mean breadth : length ratios.

Thus, whilst a new, finer-grained granoblastic fabric characterises those S6 fabrics in which there are no relict earlier fabrics, for the more common case in which S6 fabric development has involved only partial recrystallisation, earlier subfabrics in markedly flattened forms may be recognised. A more detailed description of the more common case is thus given below, consideration being essentially in two parts, namely the acid gneisses and early basic rocks; description of a small outcrop of "anthophyllite rock" incorporated in the gneiss complex is also presented.

(1) Acid Gneisses

Quartz is xenoblastic and markedly elongate in L6. In sections cut perpendicular to L6 the mean grain length is 0.45mm., and the mean breadth is 0.25mm. Within S6 domains, small xenoblastic equant quartz grains are locally abundant. These have a mean diameter of 0.1mm. Quartz is typically strained and crystal boundaries are irregular, often

sutured, but also commonly smooth and lobate.

Plagioclase feldspar has a subfabric which implies a complex developmental history. In S6 domains the most obvious feature is the zoned nature of the plagioclase. There is a gradation in composition between cores and mantles. Reverse and normal zoning are common, oscillatory zoning is frequently developed and as many as three changes of the zoning trend have been observed within a single grain (see Plate V.7b).

The cores of zoned crystals are not always centrally located within a particular crystal and numerous examples of crystals with more than one core have been observed. The cores may be either fresh or turbid. Mantles are usually fresh. Core composition varied in the samples studied from An 20% to An 32%. Zoned mantles, however, display a much narrower range in composition, generally between An 24% and An 29%, with a marked concentration at An 25% - An 27%. The anorthite content of the core thus shows a similar range to that described for the plagioclases of pre-S5 fabrics in the acid gneisses. The mantles show a much narrower range of compositional variation and are considered to represent M6 plagioclase growth about pre-M6 cores.

Albite and pericline twins are commonly developed; using the criteria of Vance (1961), the twinning is regarded as secondary glide twinning. In sections cut perpendicular to L6 the mean crystal length is 0.4mm., with a corresponding mean width of 0.25mm.

M3 plagioclase relicts are occasionally preserved on the southern limb of the Carnmore antiform, in gneisses possessing dominant S6 fabrics (see Plate V.8); such relicts increase progressively in number northwards of Loch Maree. The M3 relicts are usually turbid and contain numerous small granular epidote crystals; small muscovite flakes of post-M6 generation were frequently observed, aligned parallel to the

cleavage traces of the plagioclase relicts.

Biotite is the dominant mafic phase of the acid gneisses which have an S6 fabric. It forms both stout and slender subidioblastic flakes, sometimes homoaxially intergrown with muscovite. The statistical orientation preference of biotite flakes defines S5. Pleochroism with absorption is X - pale yellow, Z - khaki brown. The mean diameter of basal sections is 0.4mm. Most flakes have ragged outlines.

Muscovite forms slender idioblastic flakes having preferred orientation parallel to S6. The mean diameter of basal sections is 0.9mm. Crystal margins are smooth and straight parallel to $\{001\}$, but ragged in other directions.

Epidote is abundantly developed in this group of acid gneisses. Several varieties of epidote may be present within any thin section. Idioblastic and subidioblastic colourless, non-pleochroic forms having a mean diameter of 0.2mm. in basal section have commonly replaced biotite; many such epidotes have a xenoblastic core of metamict allanite. In some instances the core is fractured and cracks are filled with the mantling epidote which in turn may show evidence of several phases of growth. Where biotite is not abundant, epidote may form trails of small granular aggregates.

Ovoid xenoblasts of metamict allanite have also been observed; some of these have a major axis diameter exceeding 3mm.; they are usually surrounded by granular aggregates of epidote and clinozoisite which may be of post-M6 generation.

Hornblende is not a common mineral of the S6 acid gneiss fabric. It appears to be a static growth, blue-green, probably paragenetic variety which forms idioblastic and subidioblastic prisms with a planar, rather than linear, orientation (see Plate V.8b). Its general form and occurrence is similar to that of the static-growth M6 hornblende

described in section V.A1.

Apatite and Zoisite form xenoblastic grains seldom exceeding 0.25mm. in diameter. They occur in accessory proportions.

Sphene was observed in several specimens. It has subidioblastic or idioblastic form. Crystals rarely exceed 0.5mm. in their greatest dimension.

Iron Ore is sometimes present in the form of small irregular magnetite granules. The sulphide form is most common and small pyrite cubes replace S6 fabric elements. A thin corona of hematite usually mantles the pyrite cubes.

(ii) Early Basic Rocks

These do not appear to register M6 and D6 effects as readily as the acid gneisses.

Hornblende is the dominant mafic phase. It forms xenoblastic grains frequently enclosing small quartz and epidote granules. The mean grain diameter is 2mm. although there is considerable variation in size. Crystal boundaries are irregular with respect to feldspar, smooth and lobate towards quartz, and either straight and smooth or ragged towards biotite. Pleochroism is strongly developed X - pale yellowish green, Y - green, Z - deep blue green.

Plagioclase Relict M3 feldspars are common and xenoblastic forms predominate, the mean diameter being 2mm. These are sometimes very turbid; invariably they are crowded with small zoisite and epidote granules.

Relict M5 feldspars show many of the zonation features described in section V.D1b(i). The core compositions range from An 24% to An 35%. M6 zoned mantles have a smaller compositional range, usually about An 28%. The mean diameter of M5 plagioclase relicts is 0.9mm.

Biotite occurs as aggregates of xenoblastic grains. The mean

diameter of basal sections is 1mm. Many flakes have included quartz blebs. Pleochroism is X - straw yellow, Z - khaki brown.

Epidote in idioblastic or subidioblastic forms of a colourless non-pleochroic variety replaces biotite, but is also developed in the felsic domains. The mean diameter of basal sections is 0.2mm.

Iron Ore Small flake-like forms of magnetite are subordinate to, and enclosed by, xenoblastic and subidioblastic pyrite crystals. There is considerable size variation and some intergrown aggregates exceed 0.5mm. in diameter.

Sphene Small lozenge shaped forms occur in accessory proportions.

Quartz forms bleb-like inclusions in hornblende and biotite. It was also observed as larger globular forms along hornblende-plagioclase interfaces, or as discrete quartz aggregates. The largest patches measure 1.5mm. in diameter. Undulose extinction is characteristic.

(iii) "Anthophyllite Rock"

Outcropping approximately 1km. north of Kernsary farm and incorporated in the gneiss complex on the southern limb of the Carnmore antiform is a rock termed "anthophyllite rock" in the field.

Anthophyllite forms about 6% of the rock mode. Crystals are subidioblastic and form coarse-textured interlocking radiate aggregates. Some crystals exceed 2cm. in length. Crystal margins are straight parallel to the prismatic cleavage, but jagged and acicular in other directions.

Chlorite of a colourless non-pleochroic variety constitutes approximately 10% of the rock mode. Most crystals are polysynthetically twinned, with $\{001\}$ as composition plane. Forms are stout and xenoblastic. Some flakes exceed 1cm. in length. There is no evidence of orientation preference in the chlorite subfabric. Textural evidence

suggests that chlorite is replaced by anthophyllite and also biotite (see Plate V.9). The chlorite is therefore considered to be a static-M5 phase. Extensive post-crystalline deformation of chlorite has occurred and kinking is common.

Biotite forms about 5% of the rock mode. Both stout and slender subidioblastic forms are developed, usually replacing chlorite. Pleochroism with absorption is X - colourless, Z - lustrous greenish brown. Biotite has suffered post-crystalline deformation, but is not so intensively strained as chlorite.

Quartzo-feldspathic domains account for the remaining 20% of the mode. In discrete quartzo-feldspathic domains an equidimensional mosaic of xenoblastic polygonal grains is characteristic. The mean crystal diameter is 0.7mm. The feldspar is plagioclase (An 26%); most are fresh and show zonation effects similar to those described in section V.D4b(1). Discrete feldspar grains enclosed by anthophyllite are xenoblastic, sometimes clouded, and attain diameters of 0.3mm.

Quartz crystals in the mafic domains have irregular globular or lenticular forms. Strained crystals are common.

Tourmaline, Allanite and Apatite occur in accessory proportions.

Magnetite is the dominant ore phase; it forms small granules and irregular patches accounting for less than 1% of the rock mode.

2. The S7 and S8 Fabrics

S7 and S8 fabrics in the gneiss complex cannot satisfactorily be distinguished in the absence of mesoscopic F7 or F8 folds. Evidence already presented (see section IV.C2) suggests that over much of the complex F7 and M7 were not intensively developed.

S7 and S8 fabrics are most strongly developed in the gneisses adjacent to the Gleann Tulacha metasediments. Restricted domains of steeply-dipping penetrative S8 foliation were observed in a north-trending

belt near Kernsary farm and extending between Meall Ghiuragarstidh and Meall na Meine. Mineralogical changes mainly involve strain effects in earlier formed crystals; recrystallisation is restricted to quartz and epidote, producing a fabric which shows gradation from earlier fabrics to a well developed mylonitic foliation.

Plate V.10a illustrates modification of the S6 fabric.

Muscovite and Biotite are flexed or kinked. Granoblastic oligoclase crystals show little evidence of strain. Quartz shows features ranging in intensity from strain shadowing and the development of Boehm lamellae to the production of "shredded" grains and markedly elongate sub-grains show extremely jagged and sutured boundaries towards each other.

Plate V.10b illustrates further development of this type of fabric. Micas, especially biotite, show granulation, quartz is more finely "shredded" and shows evidence of recrystallisation. Plagioclase at this stage is also strained.

It is apparent that original compositional and mineralogical anisotropies have been important factors in the development of mylonitic fabrics. Relatively unmodified subfabrics are preserved as augen-like bodies within a mylonitised matrix. Rocks rich in plagioclase feldspar are less likely to develop mylonitic fabrics compared with rocks rich in quartz and mica, especially if the micaceous minerals are in any way segregated.

3. S9 Cataclasites

A set of non-penetrative surfaces are illustrated on Maps 3-6 as a series of "prominent crush zones". These crush zones comprise the most important cataclasite localities and are also the sites where S9 mylonitic banding is developed; they are restricted to two types of

situation, viz.:-

(i) Areas of steeply dipping foliation having a general north west - south east strike.

(ii) Areas of marked lithological contrast, in particular the gneiss-metasediment contacts near Loch Maree; locally, however, gneiss-dyke contacts are also significant in this respect.

The distribution of cataclasites and mylonites seems to reflect the areas of strongest post-dyke deformation, in that the S9 mylonites and cataclasites are geographically associated with those rocks in which other post-dyke effects are prominent.

Pseudotachylite is developed in those belts showing the strongest cataclastic effects; mesoscopically it has a grey flinty aspect and it usually occurs sub-parallel to the foliation in the gneisses, or along the boundaries between contrasted lithologies.

The sequence of pseudotachylite formation may commence with the production of irregular folds occurring within restricted domains parallel to the regional foliation. Such folds have a cataclastic fabric and are produced by inhomogeneous simple shear along foliation surfaces (see Plate V.11a).

With further deformation the folds are ruptured, usually along their limbs, and a microscopic ribbon texture is developed in the quartz subfabric. Many examples of F8 folds show such rupture and cataclasite development; indeed, the spatial association of cataclasites and F8 folding is such as to imply continuity of development.

The final stage in the process of cataclasite development is the production of zones, often many centimetres wide, concordant with the regional foliation and in which rotated fragments of gneiss are set in a matrix of mylonite, ultramylonite and pseudotachylite (see Plate V.11b).

Microscopically, most of the pseudotachylite has discordant

relationships with the structures of the host rock. Initial cataclasis produces a mortar texture (see Plate V.12a). Further development leads to fracturing of mineral grains and the localised development of irregular zones of finely comminuted material. Such zones are usually sub-parallel to the foliation in the gneisses, but individual zones are not usually persistent since they are often cut out by subsequent shear zones. Sometimes the zones of finely comminuted material display a layering sub-parallel to the margin of the sheet, probably representing the effects of mechanical segregation of the powdered constituents.

Plate V.12b illustrates a small ultramylonite sheet intruded by an irregular apophysis of partially devitrified aphanitic material, thus demonstrating the chronological order of development.

The association of pseudotachylite with ultramylonite and intensely mylonitised gneiss is considered to be indicative of the in-situ formation of a melt as a consequence of frictional heating (Park 1961), and renders inapplicable in this instance the production of pseudotachylite by a fluidisation mechanism (Reynolds 1954, Roberts 1961).

The gneisses adjacent to the crush belts frequently show the effects of retrogression. Plagioclase is very turbid. Biotite has been replaced by a penninitic chlorite whilst prehnite lenticles are commonly developed along the $\{001\}$ cleavage traces of the pseudomorphed biotite.

The ultramylonites and pseudotachylite are cut across by thin irregular sheets and networks of clear, unstrained albite, granular greenish-yellow epidote and penninite.

Iron Ore Magnetite was observed in the form of irregular inclusions in the ultramylonites. Pyrite cubes and irregular patches occur along ultramylonite host rock contacts. The formation of the

sulphide ore phase and its hematite mantle is therefore considered to post-date ultramylonite formation.

4. Acid Veins

Over much of the gneiss complex it is difficult to assess the true nature of some of the younger fabrics on account of the extent to which relict fabric elements may be preserved or modified. However, in the Poolewe area the dykes and gneisses are intruded by a series of acid sheets; individual sheets are typically only a few centimetres in width; they are discordant with S6 in the dykes, but are folded by F7 folds (see Plate VI.14) and penetrative S7 axial planar foliation is developed. The acid sheets are thus considered to possess a fabric that essentially comprises S7 elements.

Plagioclase (An 15%) which constitutes about 55% of the mode forms xenoblastic or subidioblastic crystals. Crystal margins are irregular and frequently ragged. There is considerable variation in grain size; the largest grains exceed 4mm. in diameter. Many crystals are turbid, an effect correlated with proximity to S9 crush belts.

Quartz usually comprises about 40% of the mode. The preferred dimensional orientation of the quartz grain subfabric defines S7 although many crystals are not markedly inequant. The grain size distribution ranges from minute blebs of quartz poikilitically enclosed in plagioclase crystals to xenoblastic forms exceeding 2mm. in diameter and displaying lobate margins towards partially engulfed plagioclase xenoblasts.

Microcline may be present in small amounts, both as antiperthitic exsolution products in some of the larger plagioclase xenoblasts and also as small interstitial xenoblastic forms; individual microcline crystals seldom exceed 0.5mm. in diameter.

Epidote usually forms less than 2% of the mode. Most crystals are subidioblastic and occur discretely. The mean grain size is 0.2mm. Subordinate amounts of idioblastic zoisite crystals are sometimes present.

Biotite has in most cases been pseudomorphed by penninite and prehnite. It occurs as scattered discrete subidioblastic crystals or in small aggregates. The mean diameter of basal sections is 0.7mm.

5. The Development of Late-Stage Alkali Feldspar

Brief reference has been made to the occurrence of microcline in some of the dykes of the Kernsary and Beinn Airigh Charr areas (see section IV.B2d(iv)). Textural evidence in samples of acid gneisses, early basites and metasediments, indicates that alkali feldspar formed at a comparatively late stage in the evolution of the complex. Alkali feldspar is most prominent in the acid gneisses.

a. Mineralogical Features

Microcline is the dominant alkali feldspar developed. Measured 2Vs range between -76° and -86° ; the alkali feldspar is therefore classed as Intermediate Microcline ($-2V = 60^{\circ}$ to 80°) and Crypto-Cross Hatched Maximum Microcline ($-2V = 81^{\circ}$ to 85°) (Karfunin 1966).

b. Petrological Features

When present in small concentrations (less than 5% of the mode) microcline forms irregular antiperthitic patches replacing earlier-formed plagioclase, or small clear interstitial crystals and patches having a mean diameter of 0.5mm.

Where present in greater concentrations, a complex series of mineralogical changes is associated with the microcline development. These changes may be studied in three stages:-

- (1) Rocks in which microcline forms more than 25% of the mode.

Microcline shows great variety of grain size and forms porphyroblasts which may attain several centimetres in diameter. Most crystals are xenoblastic with irregular and lobate margins. Cross-hatch twinning is usually well developed, although the existence within individual crystals of well twinned and apparently untwinned domains may reflect varying degrees of triclinicity (Laves 1950). Film and string perthites (Andersen 1928) are commonly developed. Microcline frequently forms a rim about earlier-formed plagioclase (see Plate V.13a); turbidity is characteristic of such older feldspars.

Na-feldspar in the rocks of this group occurs as exsolution lamellae in K-feldspar hosts, and also as fresh, untwinned interstitial crystals with a composition in the range An 7% to An 9%. Some large microcline xenoblasts have thin, discontinuous albitic rims. Large antiperthitic xenoblasts of Na-feldspar poikilitically include granules of epidote and zoisite, or display symplectitic intergrowth with muscovite. Other intergrowths are common, and quartz-albite intergrowths have formed on K-feldspar grain boundaries.

Quartz-zoisite and quartz-muscovite intergrowths were also observed; the muscovite crystals display marked discordance with earlier-formed S-surfaces and possess a decussate subfabric (see Plate V.13b).

Biotite is usually fresh, but where the concentration of symplectitic muscovite is high (greater than 15% of the mode) biotite has been replaced by penninite.

(ii) Rocks in which microcline forms between 15% and 25% of the mode.

Microcline shows similar form and development to that described in (i) above. Film perthites are common and most examples illustrate cross-hatch twinning.

Na-feldspar (An 8%) forms a greater proportion of the mode than in (i) above, and the textural features described in the latter section are more clearly displayed (see Plate V.14).

Quartz-albite intergrowths are common along K-feldspar grain boundaries and albite rims on K-feldspar are well developed. Relict oligoclase crystals are usually turbid but sometimes have an albitic rim; irregular patches of albite may also be scattered throughout the turbid kernel. Such patches of clear albite are usually associated with inclusions of epidote and zoisite. Similar observations have been made concerning feldspars in granitised arkose (Coombs 1950).

Quartz-zoisite and quartz-muscovite symplectitic intergrowths are common.

Biotite is usually fresh, but high concentrations of symplectitic quartz-muscovite intergrowths are associated with penninite replacement of biotite.

(iii) Rocks in which microcline forms between 5% and 15% of the mode.

Microcline usually forms interstitial crystals which have a mean grain diameter of 0.5mm.; larger K-feldspar augen are also developed and may attain diameters of several centimetres (see Plate V.17a).

Film perthites and cross-hatch twinning are typically developed.

Muscovite-quartz symplectites are not well developed and usually constitute less than 5% of the mode.

Biotite is usually fresh.

c. The Distribution of K-feldspar within the Gneiss Complex

In the Kernsary and Beinn Airigh Charr areas, north west - south east trending belts of relative enrichment or impoverishment in K-feldspar can be distinguished. The greatest concentration of K-feldspar

occurs about 1km. north of the summit of Meall na Meine and may be related to a series of pegmatoid intrusive sheets. These seldom exceed 20cm. in width and have diffuse margins. K-feldspar is the dominant constituent of these sheets (see Plate V.15). Development of K-feldspar porphyroblasts is also characteristic in the gneisses close to these sheets.

There is coincidence between the area of greatest feldspar concentration with that in which the D5 syn-tectonic migmatisation was most intense. It is possible, therefore, that some of the K-feldspar is of M5 generation.

K-feldspar is not as common a constituent of the rock fabrics in the Creag Mheall Beag and Poolewe areas. In the latter area, locally discordant north west - south east striking potash-rich pegmatite sheets, showing sharp intrusive contacts towards both dykes and gneisses, vary in width from a few centimetres to several metres. Extremely large crystals of microcline characterise the thicker pegmatite sheets.

It is possible that the potash-rich pegmatoid sheets with diffuse contacts are consanguineous with the pegmatite sheets which have sharply defined contacts. If this is the case, it is necessary to postulate heterogeneity in P-T conditions within the intrusive environment, such that the sheets which have diffuse margins may have been intruded into a relatively hot complex in which ionic mobility was high. Intrusion could therefore have occurred at a relatively early date in a cooling complex, or alternatively into a relatively hot part of the complex.

Spatial and temporal variation in partial water vapour pressure within the complex may also provide an explanation of the observed variation in the potash-rich sheets. Plate V.16a illustrates the way in

which the microcline distribution is controlled by the pre-existing foliation. The formation of microcline domains only one crystal wide, yet markedly elongate parallel to the foliation, and also the associated development of microcline porphyroblasts, is considered indicative of metasomatic introduction, probably involving aqueous solutions.

Thus on both a regional and a microscopic scale, the pre-existing foliation has been an important controlling influence on the introduction of microcline into the gneiss complex.

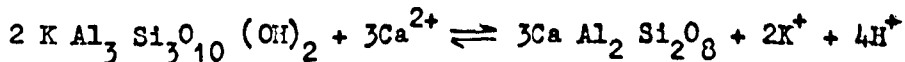
d. The Source of the Alkali Feldspar

On the basis of the petrological evidence presented (see 'b' above), it is apparent that there is a broad correlation between the development of K-feldspar and the complex mineral intergrowths involving quartz, muscovite, Na-feldspar, zoisite and epidote.

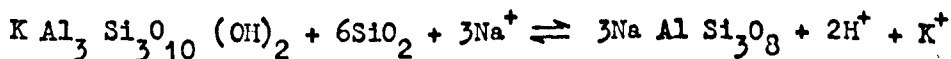
It was previously stated (see 'b' above) that the initial development of alkali feldspar results in antiperthitic replacement of oligoclase feldspar by microcline. Orville (1962) has demonstrated the readiness with which the reaction -



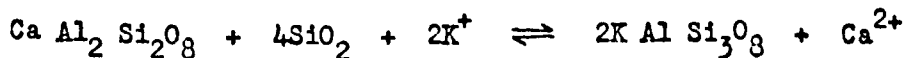
proceeds at temperatures within the range 300°C to 700°C at up to 2kb. total pressure using aqueous solutions. He also quotes other equations which "may be important in nature" but for which there is no experimental data available viz.:-



This reaction may be responsible for the sericitisation observed in some of the relatively calcic plagioclase crystals. Another possible reaction involving plagioclase feldspar is:-



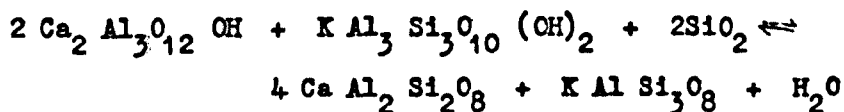
whilst the reaction:-



was proposed by Becke (1908) as the reaction responsible for the formation of myrmekite.

The implication of these equations is that an addition of K^+ ions under suitable P-T conditions may lead to the formation of K-feldspar and the release of Na^+ and Ca^{2+} ions. Released sodium could be used in the formation of albite rims on plagioclase, whilst calcium could be incorporated into zoisite or epidote.

Ramberg (1952) quotes the equation:-



in which, dependent upon P-T conditions, plagioclase is unstable in the presence of K-feldspar. These minerals react to produce zoisite, muscovite and quartz. The temperature of reaction is dependent upon the partial water vapour pressure and the Fe^{3+}/Al^{3+} ratio. Increasing water vapour pressure favours the formation of zoisite and muscovite, and a rising Fe^{3+}/Al^{3+} ratio favours the formation of epidote.

Ramberg's equation is presented because it involves most of the phases which have been observed in symplectitic intergrowth. Shelley (1964, 1967) has reviewed ideas on the formation of myrmekite; from the study of the forms and geometry of myrmekite and myrmekite-like intergrowths (including specimens of Lewisian rocks) he concludes that the intergrown minerals crystallised simultaneously, one recrystallising phase (usually quartz) being constricted by the growth of the other. Shelley argues that recrystallisation occurs as a consequence of strain. However, in the present study there is little evidence of an association of myrmekite-like intergrowths and shearing; it is therefore suggested that recrystallisation was induced by the development of disequilibrium in the system as a result of changes in the bulk rock chemistry, i.e. the suggested K metasomatism.

Implicit in the above proposal is the assumption that the initial, pre-metasomatic assemblages represented a close approach to thermodynamic equilibrium, which is upset by changes in P-T conditions or bulk rock chemistry. Similar assumptions have been made by Carmichael (1969) in consideration of reactions at metamorphic isograds; he also presents evidence which suggests that aluminium is relatively immobile in metamorphic environments; it is considered that this may be an important factor in the development of some of the complex myrmekitic intergrowths described above.

Many authors have described the petrological developments associated with alkali metasomatism in metamorphic terrains; Read (1957) presents an excellent discussion and survey of the available evidence. Commonly there is an association of introduced K-feldspar with saussuritised oligoclase rimmed by fresh albitic feldspar, replacement perthites and antiperthites, and myrmekitic intergrowths. For example, Cheng (1944) described a complex series of readjustments in the Bettyhill migmatites, and demonstrated the importance of foliation planes as a controlling influence in the formation of some of the K-feldspar.

e. The Argument for K Metasomatism

The implication of much of the above argument is that K metasomatism has initiated a complex process of mineralogical readjustments within a metamorphic environment.

It is also possible that the alkali feldspar could have been formed by metamorphic readjustments involving no net introduction of material.

Some evidence supporting an in-situ derivation of K^+ ions may be cited in the case of biotite which has been replaced by chlorite (see section 'b' above); for example Chayes (1955) has suggested that the

partial chloritisation of biotite during the hydrothermal stage of crystallisation, which is common in many granites, releases K-feldspar as a by-product. Such a reaction may have formed some of the K-feldspar observed in the acid gneisses, but it has already been stated that the chloritisation of biotite correlates with the quantity of symplectitic muscovite (see section 'b' above) and not with the amount of K-feldspar.

If this is the case, however, domains in which alkali feldspar is concentrated may be expected to correspond with lithological contrasts; available evidence however implies that there is a structural rather than lithological control affecting the alkali feldspar distribution. Furthermore, domains in which the modal proportion of alkali feldspar is low show no indication of associated mineralogical readjustments which would release K^+ ions, when compared with those domains in which K-feldspar is absent.

Thus, in summary, the positive evidence supporting metasomatism is the textural evidence of K-feldspar introduction along pre-existing foliation planes with concomitant partial replacement of older fabrics; whilst the pegmatoid sheets described in section 'c' above could provide a convenient source of such introduced material, and whose distribution correlates with the distribution of K-feldspar in the gneisses.

f. The Age of the K Metasomatism

Alkali feldspar overgrowth of S6 fabric elements implies that the metasomatism occurred after M6, or possibly during a static phase of M6. Discordant symplectitic muscovite crystals have responded to D8 by bending and kinking (see Plate V.16b). K-feldspar has also registered D8 strain. Thus the postulated metasomatism occurred after D6 and before D8 which thus corresponds in age with the development of microcline in the basic dykes (see section IV.B2d(iv)).

E. SUMMARY OF POST-DYKE METAMORPHIC EVENTS

The areal extent and intensity of post-dyke metamorphic phases is best considered with reference to the dykes themselves (see section IV.C2). The rocks of the complex into which the dykes were intruded have responded in varying degrees to the post-dyke metamorphisms and many of the observed effects have been described in preceding sections of this chapter.

1. The M6 Metamorphism

The phase assemblages described in sections V.A1, V.B1a, V.B2, V.B3a, V.C1 and V.D1, in particular the occurrence of tremolite, epidote, garnet, hornblende and oligoclase, suggest that the M6 metamorphism was in low amphibolite or upper greenschist facies.

A salient aspect of the M6 fabrics described is the complex zoned nature of the plagioclase feldspars. Goodspeed (1959) described complex zonation in metasomatic feldspars; his account shows many parallels with that presented here. However, the absence of evidence of metasomatism in many S6 fabrics which show both oscillatory and reverse zoned plagioclase suggests that an alternative mechanism may have been responsible.

Zoned crystals are common in igneous rocks and are considered to represent incomplete reaction relationships within a differentiating magma. Zoning is commonly developed in igneous plagioclase (Vance 1962, 1965) but is relatively rare in metamorphic plagioclase (Phillips 1930, Greenwood and McTaggart 1957, Jones 1961, Rast 1965, Cannon 1966). Turner and Verhoogen (1960) follow Becke (1913) in suggesting that "abundance of zoned plagioclase" is a criterion "by which diorites and granodiorites may be distinguished as magmatic in origin". Rutland et al. (1960) considered that the oscillatory zonation in the Norwegian

gneisses which they studied was a relict igneous phenomenon.

Cannon (1966) however suggested that plagioclase zonation may have a metamorphic origin, and normal, reverse and oscillatory zonation have been described in metamorphic plagioclase by Phemister (1934), Wiseman (1934), Misch (1954) and Rast (1965).

Leelanandam (1968) has reviewed the literature relating to zonation of metamorphic plagioclases and notes a correlation between reverse-zoned plagioclases and proximity to crush zones in an area of charnockitic rocks.

Miyashiro (1958), Shido (1958) and Cannon (1966) attribute reverse zoning to progressive metamorphism; Binns (1965) argues that it is due to grade dependent breakdown of co-existing hornblende. Misch (1954) suggests that conditions of low metamorphic grade and strong para-crystalline deformation are unfavourable for the development of zoned crystals in metamorphic rocks, and that reverse zoning in plagioclase may be a result of progressive metamorphism or the slow small-scale diffusion of "anorthite building" components.

Hsu (1955) explains reverse-zoned plagioclases as a response to structural differences resulting from strain and compositional differences during crystal growth.

Metamorphic crystallisation or recrystallisation involves both a nucleation stage and a growth stage about the stable nucleus (Rast 1965). Under regional metamorphic conditions nucleation and growth are influenced by the state of strain and the velocity of deformation. The slower the deformation rate, the higher the chance of nucleation of a new mineral species (Rast op. cit.).

The comparatively few examples of M6 polygonal grain fabrics (see sections IV.B2d, V.D1a) are considered to represent evidence of annealing crystallisation in response to the D6 deformation. The bulk

of M6 plagioclase growth in the gneisses appears to have occurred about pre-M6 nuclei. Comparison with the M6 recrystallised plagioclase in the basic dykes (see section IV.B2d) reveals an analogous situation. The observed oscillatory zonation in the plagioclase of both dykes and gneisses is considered to represent variations in growth conditions in response to variations in the physico-chemical conditions of the metamorphic environment, whilst the general trend from reverse zoning to normal zoning is regarded as indicative of prograde followed by retrograde metamorphic stages. These ideas therefore accord with those of Hsu (1955); by analogy with studies of igneous plagioclase it is argued that the zoned M6 plagioclase is indicative of disequilibrium in the rock system.

The M6 hornblende subfabrics of the gneisses and metasediments, and the M6 garnet and biotite subfabrics of the dykes are phenomena associated with static metamorphic conditions; there is thus no evidence in support of Binns' (1965) conclusion that metamorphic zonation in plagioclase feldspar is due to grade-dependent breakdown of hornblende; on the contrary, a possible source of components for the static M6 hornblende in the gneisses may be reactions involving M6 recrystallisation of a pre-M6 more calcic plagioclase and the replacement of biotite by epidote.

2. The M7 and M8 Events

These are associated with the metamorphic crystallisation or recrystallisation of mineral assemblages typical of the greenschist facies; calcite, quartz, prehnite and minerals of the epidote and chlorite groups constitute the minerals involved.

3. Post-Dyke Fabric Evolution

Tables V.2 and V.3 summarise some of the significant petrological features of the post-dyke complex as a whole. Data relating to pre-dyke

events are also presented for comparison purposes.

Table V.2 is based upon evidence presented in Chapters III, IV and V. It reflects observations made in a complex which is compositionally heterogeneous; moreover the spatial and temporal distribution of structural and metamorphic effects is also markedly heterogeneous and at any fixed point in time a particular phase may be recrystallising in one area and not in another. The table apparently illustrates a complex which is gradually cooling as minerals typical of the lower grades of metamorphism characterise progressively younger fabrics.

The typical shape fabric associated with each deformational and thermal event is indicated in Table V.3. Early granoblastic fabrics have been successively modified; there is a general trend of grain size reduction, and phases which typically form equant grains in the early fabrics show a progressive development towards inequant grains in later fabrics. The S₆, S₇ and S₈ fabrics show increasing development of mylonitic fabrics, leading to the ultimate production of S₉ cataclasites and the local development of pseudotachylite.

Microscopic measurements obtained of mean grain sizes in sections cut perpendicular and parallel to the dominant mineralogical lineations indicate that individual grains have a tendency towards oblate forms. Mesoscopically, however, aggregates of such grains become more prolate in the later fabrics.

The lithological heterogeneity and the inhomogeneous distribution of structural and metamorphic effects demonstrate a considerable variation in strain. High strains have occurred adjacent to lithological contacts across which there are marked differences in viscosity. Dyke-gneiss contrasts are important in this respect, but throughout the post-dyke development of the complex the lithological

contrasts between the gneisses and the Gleann Tulacha metasediments - Beinn Airigh Charr basite have formed a major structural discontinuity. Thus in M6, when growth of hornblende occurred essentially in static metamorphic conditions, M6 hornblende in the rocks adjacent to this contact is syn-tectonic.

The gneisses adjacent to the Gleann Tulacha metasediments also show more intense development of F7 and F8 folds, the finest mylonitic foliation, and some of the thickest outcrops of cataclasites and pseudotachylite.

Johnson (1967) stated that "a considerable vagueness persists on the topic of mylonites". He suggests that mylonitic banding is developed along a plane of low resolved shearing stress, and not, as is commonly assumed, along surfaces of high resolved shearing stress.

Evidence observed in the forms of curves of mylonitic banding about porphyroblasts (see Plate V.17) and relict ovoid shaped domains of earlier fabrics elongate in the mylonitic foliation, supports Johnson's hypothesis. Furthermore, Plate V.18 shows intersecting planar deformational domains within a K-feldspar porphyroblast. The bisector of the acute angle between these domains is perpendicular to the mylonitic banding. This, therefore, provides further evidence in support of the argument favouring pure shear as a means of producing a mylonitic fabric.

However, different rock materials undergoing deformation strain at different rates and in a heterogeneous complex, heterogeneous strain distribution under conditions of pure shear will result in some translative movement. The obvious sites for such movement are zones of major structural and lithological discontinuity, and the results are localised cataclasis, extreme frictional heating producing localised melting and the intrusion of pseudotachylite (Park 1961).

CHAPTER VI

STRUCTURE

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CHAPTER VI

STRUCTURE

A. INTRODUCTION

All parts of the complex show evidence of intense polyphase deformation; there are at least six phases of folding represented by both small and large scale structures.

The structural chronology has been established by study of the geometrical form of interfering fold sets, and by correlation of metamorphic fabrics.

The justification for the use of the basic dykes as stratigraphical markers has been discussed in Chapter IV. A fabric sequence was established in the dykes themselves, based upon the premise that the dykes belonged to a single swarm (i.e. whose members are not separated by any tectonic events). Study of the mutual relationships between the dykes and the gneiss complex is therefore necessary to test this initial premise, and crucial in the distinction between pre-dyke and post-dyke fabrics and structural elements.

If the initial premise that the dykes belong to the same tectonic suite is invalid, fabric and structural inconsistencies would be a necessary consequence.

B. STRUCTURAL RELATIONSHIPS BETWEEN THE DYKES AND THE GNEISSES

Fig. VI.1 illustrates sketch maps of typical structural relationships observed between the dykes and the gneisses. In the majority of cases, the N.W. - S.E.-striking foliation in the dykes is parallel, or nearly parallel, to the foliation in the gneisses and it could be suggested that these parallel foliations are coeval.

Sketch E (Fig. VI.1) illustrates a situation in which a

folded early basite is cut by a dyke. The foliation in the gneisses is axial planar to the folds of the gneissose banding, whilst the foliation in the dyke is not parallel to that in the gneisses and is clearly later (see also Plate VI.1a), so that in this case the two foliations are not the same age. In a similar way the unfoliated dyke apophyses in Fig. VI.1F cut gneisses possessing a penetrative W.N.W. - E.S.E.-trending foliation.

Other relationships are not so clear. In the weakly foliated dyke shown in Fig. VI.1D some of its initial intrusive contact relationships are preserved towards gneisses which possessed a N.W. - S.E.-striking planar fabric, but post-dyke deformation has produced similarly orientated N.W. - S.E.-striking planar structures.

Structural relationships of the type illustrated in Fig. VI.1H (see also Plate VI.1b), could be the result of one post-dyke deformational event in which N.W. - S.E.-striking planar structures were produced. Geometrically simpler solutions are possible if it is assumed that dyke intrusion was controlled by pre-existing N.W. - S.E.-trending structures. Dyke emplacement subsequently occurred along fold limbs or parallel to the axial planar foliation.

Relationships similar to those depicted in Fig. VI.1G may likewise be explained in terms of a discordant intrusion, with a limited amount of structurally-controlled emplacement induced by an existing N.W. - S.E.-striking foliation.

Although much of the evidence does not lead to a unique solution, it is sufficiently clear from many examples that the dykes cut a N.E. - S.W.-striking planar structure comprising a coarse gneissose banding; that this banding has been deformed during an event, or events, in which a N.W. - S.E.-striking penetrative foliation was imparted; and that this foliation is related to a deformational event

older than that which produced the similarly-orientated structures in the dykes.

Consideration of fabric criteria yields further supporting evidence. In areas in which the dykes are schistose throughout, the N.W. - S.E.-trending structures in the country rock gneisses have fabrics of the type described in section V.D1b and are characterised by the development of markedly inequant crystals. Country rock gneisses in those areas in which the dykes appear to be little deformed, have N.W. - S.E.-trending structures associated with comparatively equant quartzo-feldspathic subfabrics (see section III.A1).

This evidence by itself does not necessarily support the conclusion that the two fabrics are of different ages, and it could be argued that anisotropic strain rates during the same phase of deformation have produced fabric incongruencies.

An additional argument concerns the age of the migmatisation of the gneisses. In those areas in which the dykes appear to be relatively undeformed, the N.W. - S.E.-striking structures in the gneisses are associated with the development of migmatites. This migmatisation has also affected the early basite bodies (see section III.D); such bodies have similar mineralogy and composition to the dykes and would be expected to illustrate broadly congruent reactions in a common history. The fact remains, however, that without exception the dykes are not migmatised; it must therefore be concluded that an event producing N.W. - S.E.-striking structures and an associated syn-tectonic migmatisation preceded the emplacement of the dykes.

From these arguments it is concluded that N.W. - S.E.-striking foliation in the dykes is the result of a later deformation from that which produced the similarly-orientated structures in the gneisses.

Similar arguments have been used by Park and Cresswell (in press) in respect of dyke relationships in a number of other areas of the mainland Lewisian (e.g. Torridon and Tollie).

C. PRE-DYKE STRUCTURES

The pre-dyke structures are analysed within each of the four sub-areas (see section II.A) before the regional pattern is considered.

1. The Creag Mheall Beag Area

a. Planar Elements

S3 and S5 are the dominant planar elements. S3 is an irregular gneissose banding defined by variations in the proportions of the major mineralogical constituents. S5 is a finer, more regular foliation expressed in terms of the parallel alignment of quartz folia and the preferred orientation of biotite flakes.

Map 3B and Fig. VI.2a illustrate that S3 is a steeply dipping surface which displays considerable variation in strike. In the northern part of the area S3 has a relatively uniform N.N.E.-strike, but has apparently been subjected to large scale folding about N.W. - S.E.-trending axes in the south of the area. The outcrop of the various gneiss units mapped (Map 3A), clearly reflects the attitude of S3 in this area.

S3, however, is in part a transposed earlier surface, S2, and there is much evidence of F3 folding; penetrative S3 foliation is associated with some F3 folds. F2 intrafolial folds, observed in F3 fold closures of some early basite bodies, imply the existence of an earlier surface, S1. Very little may be deduced about S1, except that it is represented by a compositional layering (see Plate III.7).

Map 3C illustrates the S3 transposition of S2. In the

northern part of the area where S3 appears relatively undeformed, it is possible by construction of the enveloping surfaces for individual F3-folded horizons to deduce that the original strike of S2 was approximately N.W.-S.E.

Detailed reconstruction of the pre-F3 surface is not attempted, due in part to the completeness of the S3 transposition, but also to the complicating effects of intense post-F3 deformation. A further difficulty, as Fig. VI.2b illustrates, is the great variability in L3 attitude relative to the small number of measurements made.

b. F3 Fold Geometry

The amplitude of F3 folds varies from a few centimetres to several metres, whilst the presence of large scale F3 folds is implied in the outcrop pattern of the gneiss units mapped (Map 3A).

F3 fold axial planes are steeply-dipping surfaces displaying variable strike as a result of subsequent refolding. S3 axial planar foliation is not always associated with F3 folds and open F3 folds usually have no axial planar foliation.

L3 mineral lineations are not commonly developed. F3 fold axes tend to have steep plunges (Fig. VI.2b); this plunge variation cannot satisfactorily be explained in terms of post-F3 deformation, but is considered to be a consequence of the development of S3 upon an already folded surface.

There is considerable variation in the style of F3 folds; disharmonic, symmetric and asymmetric folds are developed, with tightness ranging from gentle to isoclinal (Fleuty 1964), (see Plate VI.2).

Small scale asymmetric F3 folds were observed on the limbs of

larger F3 structures, but it was not possible to identify large scale F3 structures by mapping the sense of asymmetry of coeval small scale structures (Ramsay 1958). The extreme attenuation of many F3 fold limbs, and the effects of intense post-F3 deformation were the main limitations in this respect.

c. F3 Folding Mechanisms

The geometrical classification of folds proposed by Ramsay (1967 pp.359-372) is difficult to apply in the case of lithological layering represented by an irregular gneissose banding which has experienced polyphase deformation; however, folds of the type shown in Plate VI.2a resemble parallel folds, whilst other folds (see Plate VI.2b) approximate to the similar fold model.

Most F3 folds approximate more to the similar type of fold model, in that the thickness of a given layer shows greater variation measured orthogonal to the layer boundary, than measured parallel to the fold axial plane.

Distinction between flexural flow and passive folding (Donath and Parker 1964) depends upon accurate geometrical description, and thus its application to the acid gneiss complex suffers the same limitations as the rigorous geometrical classification proposed by Ramsay (1967).

However, the tendency towards a relatively uniform orthogonal thickness in some of the folded layers in F3 "similar" folds leads to the conclusion that passive folding has not been the only operative mechanism. Lithological anisotropies and ductility contrasts between adjacent layers are thus considered to have played an important role in the course of the D3 deformation.

Within the gneiss complex, the greatest lithological

contrasts are between the acid gneisses and the early basic rocks.

Fig. VI.3a illustrates dip isogons constructed for an F₃ fold of mineralogical banding in an early basite body; this fold corresponds with Class 1A folds (Ramsay 1967) and is analogous to folds produced by buckling relatively competent layers.

The F₃ deformation may be thus envisaged as a progressive event involving the buckling, and in some cases disruption and agmatization, of the early basic bodies. Trondhjemitic pegmatites (see section III.D2), syn-tectonically introduced, acquired an S₃ fabric as deformation continued.

D₃ boudinage of the early basic rocks may be indicative of flexural flow-folding mechanisms, with the least ductile layers strained to the point of failure (see Plate VI.3).

Passive folding (Donath and Parker 1964) may have been operative, particularly in the acid gneisses in which there were probably no marked viscosity contrasts between adjacent layers, but since true "similar" folds were not recognised, this must remain conjectural. Since many apparently similar folds of naturally deformed rocks are considered to owe their initial development to a buckling mechanism (Biot 1961, Flinn 1962, Ramsay 1962a, Ramberg 1964), it is to be expected that true similar folds are rare in nature.

Intense homogeneous deformation (common in basement areas (Watterson 1968b)) can produce tight similar folds from open buckle folds, without continued buckling (Flinn 1962). Thus, those folds whose geometrical form resembles the flexural flow folds of Donath and Parker (1964), may have been produced by a combination of flexural slip and subsequent homogeneous deformation.

In conclusion, therefore, it is considered that the D₃ deformation was associated with a syn-tectonic migmatization and

involved an initial buckling process. Development of boudinage structures in some of the early basic rocks is considered indicative of flexural flow folding, but in the absence of strain markers, the amount and extent of passive deformation, both homogeneous and inhomogeneous has not been investigated.

d. F5 Fold Geometry

There is considerable variation in the amplitude of F5 folds.

Large scale F5 folds are illustrated by the S3 form lines (Map 3B), whilst centimetre-scale F5 folds are visible at many outcrops. The variability in S3 attitude may be largely explained in terms of F5 folding (see Fig. VI.2a,c).

F5 fold axial planes maintain a fairly constant orientation with steep north east dips and a N.W.-S.E. strike. F5 folds of the acid gneisses are usually associated with penetrative S5 foliation, although this is not usually developed in F5 folded early basites.

A b-lineation, L5, is commonly developed in the acid gneisses; its usual form is a quartzo-feldspathic rodding, spatially associated with and parallel to F5 fold axes.

F5 folds tend to be steeply-plunging structures, but they exhibit a great-circle distribution co-planar with S5 (see Fig. VI.2c). This distribution is considered to reflect the fact that D5 affected a geometrically complex surface.

Map 3D illustrates L5 lineation pitch isogons constructed with S5 as a constant reference surface; since F5 fold axes tend to have steep south east or north west pitch, it is considered most likely that the pitch direction changes through a vertical rather than horizontal attitude; the lineation pitch isogons are constructed according to this premise. It is clear that the isogons reflect the structural

trends of S3 and the importance of the S3 surface in determining the geometry of D5 structures.

F5 folds display considerable variety in style; disharmonic, symmetric and asymmetric folds are developed which range in tightness from gentle to isoclinal (Fleuty 1964).

In many cases it is not possible to apply a strict geometrical classification to F5 folds, due to the irregular nature of the gneissose banding and other anisotropies within the complex (e.g. see Plate VI.4). However, Fig. VI.3b illustrates an example of F5 folded lithological layering in an early basite corresponding with Class 1C (Ramsay 1967). The F5 asymmetric folds of an acid gneiss layer (Fig. VI.3c), have most of their dip isogons parallel, corresponding with Class 2 folds (Ramsay op. cit.); but the long limbs display some slightly convergent dip isogons (Class 1C) and the short limbs some slight divergence (Class 3).

e. F5 Refolding of Earlier Structures

F5 refolding of F3 structures has led to a variety of F3/F5 interference structures. The most common situation is that in which an F3 structure is folded approximately co-axially about steeply plunging F5 axes (e.g. see Plate VI.5) giving Type 3 interference patterns (Ramsay 1962b).

f. F5 Folding Mechanisms

The geometry of the folded layers in F5 folded early basites, and the absence of penetrative S5 foliation in these bodies, is considered to indicate that they were deformed by buckling.

In the acid gneiss complex, particularly in the north of the area, penetrative S5 foliation is sometimes present having no spatial association with mesoscopic F5 folds (see Plate VI.6a, Map 3B). It is

therefore suggested that restricted domains experienced homogeneous deformation in D5, leading to the development of penetrative S5 foliation at right angles to unfolded S3 lithological layering.

For most of the Creag Mheall Beag area, however, the lithological heterogeneity of the gneiss complex and the deformational heterogeneities expressed as F5 folds are salient features.

No strictly similar folds were observed in the Creag Mheall Beag area and D5 involved both flexural and passive folding (Donath and Parker 1964). Homogeneous deformation may have been important within restricted domains, but over most of the area D5 was heterogeneous. Associated with D5 was a syn-tectonic migmatisation (see section III.D3).

g. The D4 Event

The Gruinard metasediments outcrop in a narrow E.S.E. - W.N.W.-trending belt and have S5 as their dominant planar element. For the most part the lithological layering is co-planar with S5, but in some parts of the metasediment outcrop the lithological layering dips steeply to the north north west and is thus oblique to steep north north east-dipping S5. F5 folds of the lithological layering have steeply plunging axes.

The exact nature of the lithological layering of these metasediments is uncertain. If the lithological layering represents a post-D3 sedimentary layering, it is necessary to postulate the existence an event D4, in which sub-horizontal sedimentary layering is effectively rotated into a steep north north west-dipping attitude, before being further deformed and transposed in the D5 episode.

2. The Kernsary Area

a. Planar Elements

The dominant planar elements are S3, an irregular gneissose banding and S5 penetrative foliation.

S3 (see Map 4, Fig. VI.4a) is a moderately to steeply dipping surface, varying in strike from N.E. - S.W. to E.-W. and N.-S.

S5 (see Map 4, Fig. VI.4b) maintains a fairly uniform N.W. - S.E.-strike, but dips vary from steep to the north east in the north of the area to gentle or sub-horizontal in the south.

The S3 form lines (see Map 4), imply that there has been large scale folding of S3 and that S5 may be a penetrative foliation associated with this event. Figs. VI.4a and VI.4b may also be interpreted in terms of F5 folding of S3 accompanied by the development of a penetrative foliation, S5.

S3 is in part a transposed earlier surface S2, and there is much evidence of small scale F3 folding. The mapped form of some of the early basites (see Map 4), implies that there was also larger-scale F3 folding.

b. Linear Elements

L3 elements (see Fig. VI.4c), comprise measured small scale F3 fold axes; these display considerable variation in plunge. The majority of L3 lineations appear to be parallel to the mean attitude of S5 and are considered to have been rotated during D5 into parallelism with S5.

The L5 elements include both mineralogical b fabric lineations and small scale F5 fold axes; they have a great circle distribution (see Fig. VI.4b), parallel to the mean attitude of S5. This distribution reflects the fact that D5 affected a structurally

heterogeneous complex, analogous to a similar situation in the Creag Mheall Beag area (see section VI.C1d).

There appear to be two distinct concentrations of L5 elements. It is therefore possible that the distribution of L5 elements could represent the re-orientation of a comparatively uniformly-plunging L3 lineation during F5; the two concentrations of L5 elements would thus correspond to re-orientated L3 elements upon the respective N.E. and S.W.-trending limbs of F5 folds.

In contrast, the evidence of Figs. VI.4a-b implies that L3 had variable plunge with respect to S3, corresponding with a similar situation in the Creag Mheall Beag area. It is therefore suggested that the L5 distribution in the Kernsary area may be explained in terms of F4 folding of S3, although the F4 folding was not directly observed in terms of small scale F4 structures.

c. Fold Geometry and Folding Mechanisms

The geometry and folding mechanisms associated with the pre-dyke structures of the Kernsary area are similar to those of the Creag Mheall Beag area; for example, small amplitude F5 folds of an early basite having Class 2 fold geometry were observed; adjacent larger amplitude F5 folds however have Class 1C geometry, similar to that in Fig. VI.3b. Passive folding was therefore either limited in extent, or combined with other mechanisms of folding.

The effects of D5 syn-tectonic migmatization are also extensively developed in the Kernsary area. The progressive nature of this migmatitic event and the structures associated with it were considered elsewhere (see section III.D3).

3. The Beinn Airigh Charr Area

Comparatively few of the pre-dyke structures in this area are preserved except in extremely modified forms.

In the gneiss complex, S5 is the dominant pre-dyke planar element and is most extensively preserved on Creag Cairneasair as a sub-horizontally disposed foliation; small-scale F5 folds of the S3 gneissose banding are developed; these have sub-horizontal axial planes and penetrative S5 foliation. Larger-scale F5 folding is demonstrated by the mapped form of the early basite bodies on Creag Cairneasair (see Map 5A).

Small-scale F5 folds were observed in the Gleann Tulacha metasediments, but are most commonly preserved in the Beinn Airigh Charr basite as isoclinal folds of a compositional layering (see Plate VI.6b); a b-fabric lineation, L5, is defined by the alignment of acicular hornblendes.

The intense and polyphase nature of the deformation that subsequently affected the Gleann Tulacha metasediments and the Beinn Airigh Charr basite makes it difficult to deduce the nature of the pre-D5 layering or the original attitude of S5.

4. The Poolewe Area

a. The Pre-Dyke Structural Sequence

The pre-dyke structural sequence in this area is different to that described elsewhere and correlation with the other areas considered is necessarily less securely based.

One of the oldest S-surfaces is preserved in a few localities in the south east part of the area, particularly near Croft Hill (856795); this surface is an irregular gneissose banding whose attitude varies, but approximates to a N.E. - S.W.-strike with steep S.E. dips. The

attitude of this surface thus corresponds with that of S3 in the Creag Mheall Beag and Kernsary areas (see Fig. VI.5a).

It is apparent that S3 has been affected by F4 folding; the F4 folds have amplitudes of several metres, they are asymmetric structures in which the shorter limbs have steep northerly dips. S4 is the foliation which is developed parallel to the thinned limbs of F4 asymmetric folds. Only a few measurements of S4 have been recorded in view of its restricted outcrop (see Fig. VI.5a).

Both S3 and S4 have been affected by small scale F5A folds which have steeply-dipping axial planes striking E.S.E. - W.N.W.

For the remainder of the Poolewe area there is little evidence of either S3 or S4. In the north and west of the area, the oldest surface, an irregular gneissose banding, has been folded about sub-horizontal axes. These folds are close to tight (Fleuty 1964) and have sub-horizontally disposed axial planes and axial planar foliation. In a few cases it is apparent that these recumbent folds refold earlier folds of the gneissose banding and that the latter folds had steeply dipping axial planes.

The fabric associated with the sub-horizontal foliation corresponds with the S5 fabric recognised elsewhere; this S5 foliation has, however, been folded to produce steeply dipping N.W. - S.E.-striking planar structures, which have been correlated with S5A recognised in the south east of the Poolewe area.

It is therefore considered most likely that the sub-horizontal foliation in the north and west of the Poolewe area is S5, but that this, for the most part, has been steepened up during D5A.

b. The Geometry of the Pre-Dyke Structures

Plate VI.7 illustrates the style of F5A folding, whilst

Plate VI.8 illustrates a typical example of F5A superimposition upon F5 structures.

S5A has a fairly uniform N.W. - S.E.-strike and steep N.E. dips, whilst the L5A b-fabric lineations display considerable variations in plunge, although most lineations plunge south east (see Fig. VI.5b).

Lineation pitch isogons have been constructed for the L5A lineations (see Map 6B), in order to investigate the variability of lineation attitude (Elliot 1965, Park 1969a) with respect to the S5A surface.

In the north of the area the isogon pattern is relatively simple, with pitch increasing from west to east; the trend of the isogons is oblique to that of the S5A foliation form lines. There is clearly no unique explanation of this lineation distribution.

It could be suggested that sub-horizontally disposed S5 experienced large scale folding about E.S.E. - W.N.W.-trending axes, prior to the imposition of the steeply dipping N.W. - S.E.-striking S5A foliation; the L5A lineation would in this case represent the intersection between the S5 and S5A surfaces. Objections can be raised to this hypothesis on the grounds that there is no evidence of large scale post-F5, pre-F5A folding.

Another model may be proposed in which the steepening of the L5A lineation is associated with progressive D5A flattening of the S5 surface folded in F5A. This hypothesis does not require the additional deformational episode of the previous model; there is, however, no evidence of progressive flattening, either in terms of a tendency for F5A folds to become progressively tighter with increasing lineation pitch, or in the form of any fabric evidence. For these reasons, this model is also considered unlikely.

A third model assumes that the S5 transposition of steeply dipping pre-S5 surfaces increases from east to west, and thus S5A is developed upon a complex surface, in part dominated by S5, in part dominated by pre-S5 surfaces. The L5A lineation thus represents the intersection between S5A and a compound pre-S5A surface. This model is considered to be preferable to the others since in the south east of the Poolewe area, S3 rather than S5 appears to be the dominant planar element - i.e. S5 is not a penetrative structure within the Poolewe area as a whole.

In the south of the area the isogon pattern is more complex, and interpretation is necessarily speculative.

The elongate domes and basins which characterise the pattern may be interpreted as a consequence of inhomogeneous flattening in D5A, or may represent the tendency for L5A pitch to be extremely sensitive to small variations in the attitude of the pre-D5A surface, when the dips of this latter surface are steep (c.f. Park 1969a). The apparent east west trend of some of the isogons in the south of the area may be illusory, in view of the narrowness of the outcrop belt. Relicts of a surface which is possibly S3 may be indicative of the fact that S5 was not developed as a penetrative structure in this part of the Poolewe area and that S5A was superimposed upon steep easterly trending structures; no evidence was observed, on a mesoscopic scale, in support of this and it is necessary to admit the possibility that the variation in attitude of S5 foliation may be an original feature.

The existence of a D4 event has been inferred from structural analysis of the Creag Mheall Beag and Poolewe areas. The limited evidence available suggests that in the Poolewe area, S4 had an approximate E.-W.-strike and steep dips. If, in the Kernsary area, S3 had a N.E. - S.W.-strike and steep dips, and if S4 was developed in

this area with a similar attitude to S4 in the Poolewe area, the intersections of S3 and S4 with the mean attitude of S5 in the Kernsary area are lines corresponding with the two main concentrations of L5 elements (c.f. Fig. VI.4b with Fig. VI.5a). It is therefore tentatively suggested that F4 affected the Kernsary area, and that the gneissose banding, recorded as S3, may be in part S4 transposition of S3, with the precise relationships between these latter surfaces obscured during D5.

Finally, within the Poolewe area S5A foliation was developed and S5 was locally steepened during D5A, prior to the intrusion of the dykes. Comparable structures were not observed in the other areas.

D. STRUCTURAL CONTROL OVER DYKE EMPLACEMENT

Over much of the area the dykes appear to be intruded sub-concordantly with S5 and although many dykes have a foliation parallel to S5, structural and fabric criteria imply that the foliation in the dykes post-dates S5 - a situation apparently common in other areas of the southern district of the mainland Lewisian outcrop (c.f. Park and Cresswell (in press)).

The form of the dykes appears to have been controlled by the nature of S5. Where S5 is a set of finely-spaced S-planes, individual dykes appear to be narrow and the dihedral angle between branches is small; where S5 is a less closely-spaced penetrative structure, individual dykes are thicker and have a correspondingly larger dihedral angle between dyke branches. This situation is well illustrated in the Creag Mheall Beag area (see Map 3A), where there is an obvious contrast in outcrop pattern between the Second-Period dykes which intrude the Gruinard metasediment tract, having closely-spaced S5, and the Second-Period dykes in the north of the area.

There is a different structural pattern in the Poolewe area,

where most dykes form sheets sub-concordant with S5A. Plate VI.1b illustrates a dyke intruded parallel to the limbs of F5A folds, providing criteria for distinction between S5A and the internal foliation of the dykes. The form of the dykes in the Poolewe area is also different to that observed elsewhere in the complex; in the west of the area there is a large number of thin dykes in which it is often difficult to detect discordance with S5A (see Plate VI.9). In the east the intrusions are thicker and have a complex form with numerous branches and offshoots, mostly concordant with S5A. Some of the thicker dykes contain narrow screens of gneiss, often little more than 1cm. thick but which persist for several metres along the strike (see Plate VI.10a): these screens maintain the local S5A orientation.

Thus for the Poolewe area S5A appears to have exerted a strong structural control over dyke emplacement.

E. POST-DYKE STRUCTURES

1. D6 Structures

S6 is the oldest foliation recognised in the dykes, and is best developed in the dykes of the Beinn Airigh Charr and Poolewe areas. When penetrative through the whole dyke body, and when unaffected by subsequent deformation, S6 has a N.W. - S.E.-strike and is thus sub-parallel to S5, S5A and the dyke margins.

Where S6 is not penetrative through the whole dyke body, the foliation is confined to dyke margins and has a sigmoidal form; near the contacts S6 is sub-parallel to the dyke margin, but becomes oblique to this direction towards the centre of the dyke.

Sigmoidal forms of S6 foliation in the dykes are best developed in the Creag Mheall Beag area, and in some narrow dykes in this area this type of foliation is continuous throughout the dyke

body (see Plate VI.10b).

Fig. VI.6 indicates plots of the dihedral angle between the internal foliation of the dykes and the attitude of dyke contacts, for measurements made in the Creag Mheall Beag area. It is apparent that the internal foliation of the dykes is comparatively constant in attitude when compared with the variability in attitude of the dyke contacts, although the internal foliation bends into parallelism with the contact adjacent to the dyke margins.

The simplest interpretation of these features is that the foliation in the dykes formed at right angles to the principle axis of shortening within the complex as a whole (Ramsay and Graham 1970, Berger 1971) and thus dykes making a large angle with this direction have large dihedral angles. The tendency for the internal foliation in the dykes to become asymptotic to the dyke margins may be explained as a boundary effect, probably controlled by strain rate, amounts of stress, and viscosity contrasts between the dykes and host rocks (Watterson 1968a).

The mean attitude of the internal foliation in the dykes of the Creag Mheall Beag area is a 75° north east dip with a 130° strike azimuth; if the principle axis of shortening is thus assumed to have had a sub-horizontal disposition and a N.E. - S.W. orientation, it would be expected that dykes which had a N.-S. or N.W. - S.E.-strike would display an 'S' pattern of their internal foliation, indicating an effective dextral displacement of their sidewalls; dykes having a E.-W. or N.E. - S.W.-strike would, however, display a 'Z' pattern of their internal foliation, indicating effective sinistral displacement of their sidewalls. This is precisely the situation which obtains in the Creag Mheall Beag area; moreover the gneisses of the Creag Mheall Beag area contain N.-S.-trending steeply-dipping planar zones, spaced a

few centimetres apart, which may be considered penetrative on a macroscopic scale. Within these zones earlier structures appear to have been rotated and attenuated; the sense of displacement across such zones is always dextral (see Plate VI.11); they affect all pre-dyke structures, and their sense of displacement is consistent with the pattern observed for S6 within the dykes.

Within each zone the foliation is oblique to the zone margin and strikes relatively N.W. - S.E. compared with the N.-S.-trend of the zone margins. They are interpreted as a regular set of shear zones whose geometry is consistent with the principle axis of shortening deduced for D6.

L6 structures are not well developed in the amphibolite dykes of the Creag Mheall Beag area; most crystals display a planar arrangement defining the internal foliation. Linear hornblende is apparent, mainly at dyke margins, and in most cases is parallel to the local L5 attitude.

Apart from the Creag Mheall Beag area, D6 does not appear to have produced mesoscopic F6 folds in the acid gneiss complex; S6 in the gneisses has thus been recognised on the basis of fabric criteria (see section V.D). In the dykes, S6 is generated parallel or sub-parallel to the dominant foliation in the gneisses, usually S5, with which the dyke bodies themselves are broadly concordant.

In the Beinn Airigh Cherr and Kernsary areas, S6 becomes increasingly penetrative south of the S5 "flat belt" near Meall na Meine. Within this flat belt the S6 foliation in the dykes is defined by a planar orientation of hornblende crystals, but towards the south west as the southerly dips steepen a linear hornblende subfabric is progressively developed in the dykes.

S6 has been subjected to extensive post-D6 deformation (see Maps 4, 5A, 5B). However, in the south east part of the Kernsary area and in the north of the Beinn Airigh Charr area, S6 is relatively little modified by subsequent deformation; in this area the L6 hornblende lineation in the dykes has a large pitch with respect to S6, ca. 70° south east; L6 thus makes a large angle with the fold axis which generates a steep S.W.-dipping S6 surface from sub-horizontally disposed S5.

The contacts between the gneiss complex and the Gleann Tulacha metasediments - Beinn Airigh Charr basite are best displayed in the finger-like projection of the acid gneiss outcrop into the metasediment-basite outcrop at grid square 9076 (see Maps 5A, 5B): in this area, the metasediments adjacent to the gneisses contain numerous small-scale F6 folds (see Plate VI.12), whilst a large-scale F6 closure within the Beinn Airigh Charr basite has been mapped about the south-eastern extremity of the metasediment outcrop at 906765 (see Map 5B).

There are numerous small-scale F6 folds within the Beinn Airigh Charr basite; these fold S5 and the L5 hornblende lineation; the style of these varies from close flexures to chevron folds (see Plate VI.13). Ramsay (1967 pp.437-456) on the basis of a geometrical analysis of chevron folds, suggested that they characteristically form in thin bedded or finely foliated rocks under the action of a compressive stress acting along the layering. He regards them as a flexural slip phenomenon, a conclusion supported by the experimental work of Paterson and Weiss (1962, 1966).

Measurement of the interlimb angle of F6 chevron folds in the Beinn Airigh Charr basite commonly gives values in the range 25° - 30° , that is considerably less than the common value of 60° quoted by De Sitter (1958). However, the layer thickness : limb length ratios

measured on hand-specimen-size F6 chevron folds typically range from 0.005 to 0.015, and in the example shown in Plate VI.13a the ratio is as low as 0.001. Such values are equivalent to a crustal shortening of about 75% (Ramsay 1967 p.442). The widespread occurrence of F6 chevron folds within the Beinn Airigh Charr basite is therefore considered to be indicative of considerable crustal shortening during D6.

No small-scale F6 folds were observed in the acid gneiss complex of the Kernsary and Beinn Airigh Charr areas; instead D6 resulted in large-scale asymmetric folds, whilst the two prominent crush belts indicated on Map 5A correspond with the steep north east limbs of major F6 antiformal structures. The pseudotachylite in these crush belts is unmetamorphosed and obviously post-dates D6; the association of pseudotachylite with the steeply dipping limbs of major F6 folds is considered to be an example of the structural control exerted by pre-existing structural anisotropies.

The S6 fabric is best developed in the steeply-dipping belts of S6 in the Beinn Airigh Charr area. They represent the sites of intense D6 flattening, in turn related to large scale shear zones in the gneiss complex and are analogous with the D6 structures in the gneiss complex of the Creag Mheall Beag area, where most of the strain is concentrated in zones of intense flattening.

The kinematic significance of the L6 lineation in the dykes of the Kernsary and Beinn Airigh Charr areas is uncertain. The progressive development of this lineation with increasing S6 dip could be interpreted as the result of extrados circumferential elongation on surfaces bent into the steep S6 attitude, the lineation itself defining the direction of maximum elongation during D6.

In the Poolewe area, S6 is difficult to identify in the gneisses but in the dykes it is a steep N.E.-dipping surface, broadly

parallel to S5A in the gneisses (see Figs. VI.5b-c). The majority of the dykes in this area were intruded parallel to S5A; S6 is therefore commonly parallel to the dyke margins. Where the dyke margin is oblique to S5A, S6 tends to remain parallel to the margin, although this effect becomes progressively less apparent towards the centres of such dykes.

Figs. VI.5b-c demonstrate that the L6 hornblende lineation in the dykes is parallel to the L5A lineation; it therefore seems likely that pre-existing anisotropies have been an important control during D6.

2. D7 Structures

These are restricted to the Beinn Airigh Charr and Poolewe areas. In the Poolewe area, small-scale tight F7 folds affecting S6 and post-D6 granitic veins have been identified (see Plate VI.14a). Penetrative S7 foliation in these veins is defined by recrystallised quartz crystals. F7 folds are commonly associated with bifurcations in the dykes; at such points, S6 in the dykes probably developed obliquely towards the regional trend and parallel to the dyke margins (see section VI.E1). Since S7 structures are generally co-axial and co-planar with L6 and S6 respectively, localities where S7 is oblique to S6 are the sites at which F7 folds would be expected. No large scale F7 folds of the dyke outcrop are apparent; this is considered to be a consequence of the co-planarity of S5A and S7, and is further evidence supporting the hypothesis of structurally controlled dyke emplacement, parallel and sub-parallel to S5A.

F7 folds in the Beinn Airigh Charr area have been recognised from evidence of interference structures (see Plate VI.14b). There are many similarities in style between F7 and F8 folds and it is not always possible to distinguish them. Penetrative S7 axial-planar foliation is restricted to the calcareous rocks of the Gleann Tulacha metasediment group. S7 foliation and F7 axial planes are steeply inclined surfaces

having a general N.W. - S.E.-strike. Fold axes display considerable variation in plunge, a factor attributed to the development of F7 folds upon the geometrically complex pre-D7 surface.

Over much of the Beinn Airigh Charr area it is difficult to distinguish F7 and F8 folds using fabric criteria. Within the area of Map 5B, the attitude of F7 and F8 fold axes (see Fig. VI.7a) display a broad scatter within the north west and south east quadrants of the stereogram; moderate or steep plunges predominate. Analysis of the orientations of the small-scale F7 and F8 folds within this area suggested that they could be distinguished by their orientation, in that where both fold sets occurred in association, F8 folds were smaller-scale and N.-S. or E.S.E. - W.S.W.-trending structures superimposed upon larger-scale N.W. - S.E.-trending F7 folds. Both the F7 and F8 structures have steeply-dipping axial planes.

Intensive sampling within the area of Map 5B indicates a crossed girdle pattern for poles to the dominant S-surface (mainly S5 transposed by S6, but refolded in D7 and D8). Sub-area analysis (see Figs. VI.8a-c, Fig. VI.7b, and Map 5B) produces an almost complete separation of the crossed girdles into two simple girdles. Also in each of the sub-areas, the dominant mineral lineation gives concentrations corresponding with the respective girdle axes (see Fig. VI.9a-c). Thus for the south-western sub-area, the major structure plunges moderately steeply to the north west, a pattern also demonstrated in the central sub-area. In the north-eastern sub-area the major structure plunges moderately steeply south east.

The dominant mineral lineation, within the area of Map 5B, is L5; within the Beinn Airigh Charr basite, from which most of the readings for Figs. VI.8 and VI.9 were obtained, F6 chevron folds fold the L5 hornblende lineation such that the lineation pitch on respective F6 fold

limbs is approximately 60° with respect to F6 axes. Plots of F7 and F8 fold axes (see Fig. VI.7a) indicate similar concentrations and distribution as the refolded L5 elements; F7 and F8 axes thus appear to be approximately co-axial with the folded L5 lineations.

Thus the finger-like projection of the acid gneiss outcrop, in the area of Map 5B, is interpreted as a major F6 antiform which caused the rotation of sub-horizontal S5 into a steeper attitude, and folded the L5 lineations, such that the lineation plunge on adjacent fold limbs was of similar magnitude. The major F6 fold axis is thus considered to have been sub-horizontal, perhaps with slight plunge towards the south east.

Sub-areas (1) and (3) of Map 5B are interpreted as major F7 structures. In these sub-areas small-scale F6 chevron folds have been refolded by F7 folds (see Plate VI.15). The F7 fold axes are co-axial with the mean orientation of the folded L5 lineations and thus, although F7 folding causes some spreading of the L5 lineation plots it does not fundamentally alter the distribution of this lineation that resulted from F6 folding.

F8 folds were superimposed upon a pattern of steeply-dipping surfaces and steeply-plunging lineations; they therefore do not appear to have fundamentally affected the lineation patterns. W.N.W. - E.S.E.-trending F8 folds are most common in sub-area (1); N.-S.-trending F8 folds are most common in sub-area (3), although F8 fold sets having both trends occur in all three sub-areas.

For the remainder of the Beinn Airigh Charr area the geometry of S6, the prominent mineral lineation and the F7 and F8 folds appear to be closely analogous with those of sub-area (3) (see Figs. VI.10a-c) and record a similar deformational history. The hornblende lineation in the dykes is thus interpreted as being developed parallel to an older,

probably L5, lineation in the acid gneiss complex.

3. D8 Structures

These have already been considered in detail for the Beinn Airigh Charr area. Fig. VI.11a-d, indicates the style of some F3 folds from the Beinn Airigh Charr area, implying an origin by buckling.

A large scale asymmetric F3 fold is located in the south west of the Kernsary area (see Map 4); smaller scale F3 folds are associated with this, and most are likewise asymmetric. Locally there is transposition of earlier formed S-surfaces into the steeply-dipping N.-S.-striking S3 direction.

F3 folds are sometimes developed in the finely foliated marginal portions of the dykes of the Kernsary area; these folds have upright N.-S.-trending axial planes.

In the Poolewe area, F3 folds are steeply-plunging with steeply-dipping axial planes; when viewed on a horizontal outcrop surface, the axial planes have either a N.-S. or E.S.E. - W.N.W.-trend and resemble in style and attitude the F3 folds of the Beinn Airigh Charr area.

F3 folds in the Poolewe area are associated with varying degrees of disruption and there appears to be a progressive development from F3 folding towards ultramylonites and pseudotachylite; this is particularly noticeable in the N.W. - S.E.-trending crush zone indicated on Map 6A. In this zone, F3 folds, disrupted F3 folds, ultramylonites and pseudotachylite are all intimately associated. A similar correlation of F3 folding and pseudotachylite localities was observed in the Beinn Airigh Charr area. Thus for the Croag Mheall Beag area in which evidence of F3 folding is slight, the presence of prominent crush belts associated with pseudotachylite development may represent a

record of D8 deformation. Alternatively, if the post-dyke deformational events are considered as stages of a progressive deformation, it is possible that conditions in the Creag Mheall Beag area were such that pseudotachylite was developed there whilst the rest of the complex was experiencing D7 deformation.

CHAPTER VII

CONCLUSIONS

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CHAPTER VII

CONCLUSIONS

In the preceding chapters detailed evidence, concerning the geology of the Lewisian rocks studied, is presented; and some of the more obvious conclusions drawn on the basis of this evidence are discussed. This chapter therefore summarises some of the more important aspects of the geological history, and attempts to correlate these findings with recent work undertaken in adjacent areas.

A. CHRONOLOGY

1. Pre-Dyke Events

The pre-dyke development of the tectonite fabric was discussed in Chs.III and VI.C. Deformational events D1, D2, D3, D4 and D5 are associated with structural surfaces S1, S2, S3, S4 and S5 respectively. S3 and S5 are the dominant pre-dyke planar structures with L3 and L5 the dominant linear elements associated with both small and large scale F3 and F5 folding of earlier planar structures. S3 and S5 have a dominant strike of N.E.-S.W. and N.W.-S.E. respectively. S3 dip is usually steep whilst S5 displays a range in dip from steep to sub-horizontal.

The pre-dyke metamorphic fabric is mainly the result of the M3 and M5 events; M3 was in part in granulite facies, whilst M5 was entirely in amphibolite facies. Post-D2 to pre-D3, D3-syn to post-tectonic, and D5 syn-tectonic migmatite events are recognised; the neosomes associated with these events are dominantly trondhjemitic and there is little evidence of widespread anatexis.

Rocks of presumed sedimentary origin, the Gruinard and Gleann Tulacha metasediments, are spatially associated with hornblende schist bodies, the Gruinard and Beinn Airigh Charr basites. Contacts between these rocks and the acid gneiss portions of the complex are often poorly exposed or completely unexposed. Where such contacts are directly observed, they appear as zones in which strain has been concentrated, so that the original contact relationships between the gneisses and the metasediments have been destroyed. Thus the chronological status of the metasediments and associated basites cannot be established directly.

Neither the metasediments nor the associated basite sheets show evidence of the high-grade M3 fabric elements, nor do they show the effects of pre-dyke migmatization observed in the adjacent acid gneisses. F5 folds of the compositional layering are the oldest metamorphic structures observed in the metasediments and basites. In the Gruinard metasediments and basite, F5 fold axes are steeply plunging, implying that the compositional layering (presumably bedding) was steeply inclined prior to F5 folding, thus indicating a pre-D5 deformational event in the Gruinard metasediments which may be coeval with the D4 event in the acid gneisses. Thus the metasediments and basites are considered to post-date D3 and pre-date D5.

2. The Dykes

A suite of basic dykes, now amphibolites post-dates D5 and pre-dates D6. Intrusion was not a single event, and three phases of basic dyke injection have been recognised in the Creag Mheall Boag area. Evidence of cross-cutting relationships is less abundant in the other areas mapped, but is sufficiently clear to indicate that there was more than one phase of injection.

The geochemical variation in the dyke samples analysed can be explained in terms of the differentiation of a magma having tholeiitic affinities (See Ch.IV.D.).

The basic dykes intrude the Gruinard metasediments and basite, thus confirming their pre-dyke age. The pre-dyke age of the Beinn Airigh Charr basite and the Gleann Tulacha metasediments is not so clearly demonstrated since the basic dykes do not appear to have intruded them.

3. Post-Dyke Events

Three metamorphic and deformational events, D6, D7 and D8 have affected, and therefore post-date, the phases of dyke intrusion (see Chs.V and VI.E.).

S6 is recognised as the first foliation in the dykes and is associated with L6 mineral lineation of hornblende crystals. S6 dip is usually towards the south-west, but varies from being steep to sub-horizontal in attitude. F6 folds are uncommon in the acid gneisses, except for small-scale asymmetrical folds in the Creag Mheall Beag area; S6 has therefore been distinguished mainly by its associated fabric. Small-scale F6 folds occur in the Gleann Tulacha metasediments; in the Beinn Airigh Charr basite these are chevron in style. D6 also involved large-scale folding of the contact between the acid gneisses and the Gleann Tulacha metasediments and the south-west limb of the Carnmore antiform is considered to be a large-scale F6 structure. M6, the metamorphic event associated with the D6 deformation, was in amphibolite facies.

F7 folds are most common in the Beinn Airigh Charr and Poolewa areas. Penetrative S7 foliation is not always developed and is dependent upon the rock type; it is common in the quartzites and marbles

of the Gleann Tulacha metasediments and also in F7-folded thin granite sheets in the Poolewe area, but is rarely developed in F7-folded amphibolites. F7 folds usually have steeply-dipping axial planes, striking N.W.-S.E. The intensity of M7 increases in a south-easterly direction in the Poolewe and the Beinn Airigh Charr areas (see Ch.IV.C.).

A K-metasomatic event, leading to the development of quartz-muscovite symplectites, large discordant muscovite crystals and K-feldspar blastesis, separates the D6 and D7 episodes. S6 was an important structural control over the distribution of the metasomatic K-feldspar (see Ch.V.D5.). D7 has affected the minerals associated with this metasomatic phase. Potash-rich pegmatites and thin granitic sheets which occur in the Poolewe area occupy a similar position in the chronology of events and were intruded after D6, but before D7.

F8 folds are most commonly developed in the Beinn Airigh Charr area; they vary in style from open buckles to tight folds having penetrative S8 foliation, and occur on both mesoscopic and macroscopic scales. In the Kernsary area F8 folds have steeply dipping axial planes striking N.-S. In the Beinn Airigh Charr and Poolewe areas F8 folds have steeply dipping axial planes, one set striking N.-S. and another set striking N.W.-S.E.

S8 fabrics tend to be mylonitic and ribbon textures are commonly developed in the quartz subfabrics. The accompanying metamorphism was in greenschist facies. Field relationships imply a genetic relationship between disrupted F8 folds and belts of pseudotachylite and ultramylonite. Locally within these "crush belts" a new mylonitic foliation, S9, has been imparted.

B. REGIONAL CORRELATION OF THE STRUCTURAL SEQUENCE

Table VII.1 indicates the structural sequence proposed by the writer, together with sequences proposed by various authors for adjacent

areas and the general chronologies of Sutton and Watson (1969) and Park (in press).

Correlation rests primarily upon the use of the dykes as stratigraphical marker horizons, and despite the criticisms which may be levelled at such an approach, the dykes appear to represent the best time marker in the Lewisian complex.

The regional correlation of successive phases of pre-dyke and post-dyke structures is, in principle, less securely based. Similarities in the chronology of structural and metamorphic events forms the basic criterion of the tentative correlations outlined.

Steeply dipping N.E.-S.W. or N.-S. striking gneissose banding has been correlated with PS3 of Park (in press); Cresswell (1969) and with the dominant Scourian planar structures of Sutton & Watson (1951).

In all of these examples the associated metamorphic fabrics suggest that metamorphism was in granulite or upper amphibolite facies.

S5 is correlated with I.S.1 of Park (in press) and S4 of Cresswell (1969), all of which can be correlated with the N.W.-S.E. striking foliation in the Lochinver "type area" of the Inverian (Evans 1965) and associated metamorphic fabrics developed in amphibolite facies.

The chronology of post-dyke events is conditioned by the stratigraphical status that individual workers have attached to the basic dykes. In Chapter IV it was argued that dyke intrusion was a single protracted event; thus although several phases of dyke injection have been recognised on the basis of cross-cutting relationships, no major tectonic episode separating successive phases of dyke injection has been detected. Such is essentially the viewpoint of Sutton and Watson (1951-1969) who regard the basic dykes as a stratigraphical indicator, enabling

distinction to be made between pre-dyke (Scourian) and post-dyke (Laxfordian) events.

Most workers who regard dyke intrusion as a single protracted event record three Laxfordian structural and metamorphic events in the Southern District of the Lewisian (see Table VII.1); this results in comparable sequences of fabric evolution.

The first Laxfordian event is associated with the oldest metamorphic planar and linear structures in the dykes, produced during metamorphism in amphibolite facies. The second Laxfordian event is less extensively developed and the metamorphism was in low amphibolite or greenschist facies. Metamorphism during the third Laxfordian event was in greenschist facies. Fabric evolution throughout the Laxfordian demonstrates the increased significance of cataclasis and mylonitic fabric development in successively younger fabrics.

It is thus considered that the D6, D7 and D8 events, recognised here, were widespread in their effects upon the Southern District of the Lewisian. Precise correlation of events is not possible in every case. Park (in press) records a local K-metasomatism of late-Laxfordian age, broadly correlatable with the K-metasomatic event described in the Torridon area (Cresswell 1969). However, textural evidence in the Kernsary area suggests an earlier i.e. post-D6, pre-D7 age for a similar event.

Two specimens (SM/67/53) and (GHI/20724) dated by Moorbath and Park (1972) contain "discordant" muscovites with K-Ar dates of 1516 ± 30 m.y. and 1478 ± 30 m.y. These discordant muscovites occur in association with microcline porphyroblasts. In view of the proximity of the source of these dated samples to the area studied by the author, and the textural similarity between these samples and some of the metasomatic fabrics described in the Kernsary area, it is argued that

these dates support the post-D6, pre-D7 age of the K-metasomatic event.

Correlation with the Laxfordian sequences of workers who consider that successive phases of dyke injection were separated by tectonic episodes (e.g. Bowes 1968a) is necessarily speculative since such chronologies rest upon hypotheses incompatible with those adopted in this thesis.

C. CHRONOLOGICAL STATUS OF THE ROCKS OF PRESUMED METASEDIMENTARY ORIGIN

Two groups of presumed metasedimentary rocks have been described, namely the Gruinard and Gleann Tulacha groups.

Detailed contact relationships between the metasediments and the gneiss complex are not usually exposed; where they are exposed it is apparent that subsequent deformation has been concentrated along the contact zones, thus obscuring the original relationships.

In both groups, however, S5 fabric elements have been identified, thus implying a pre-dyke age for these metasediments. In the case of the Gruinard group, the dykes cut the lithological layering and convincingly demonstrate a pre-dyke age for this group.

Neither group of metasediments has been migmatized, nor appears to show any evidence of relict high-grade metamorphic fabrics, despite the abundance of such evidence in the adjacent acid gneisses. It therefore seems unlikely that the metasediments were involved in the M3 migmatite complex.

Both metasediment groups are therefore considered to post-date D3 and pre-date D5. The relatively simple distribution of the metasediments in two main N.W.-S.E. trending outcrops, whose overall shapes can be entirely explained in terms of D5 and post-D5 deformation, is further evidence in support of this conclusion. Had large-scale M3 folding affected the Gruinard and Gleann Tulacha metasediments, a more

complex distribution of metasediments would seem likely.

Both groups of metasediments thus represent a post-D3 cover assemblage, i.e. a post-Badcallian assemblage unconformable upon the Badcallian basement; furthermore, since both metasediment groups occur at similar structural levels it is suggested that they are stratigraphically equivalent.

Calcareous rocks are absent from the Gruinard assemblages, but in both the Gruinard and Gleann Tulacha groups there is an association of quartzites and mica schists with amphibolite sheets, (i.e. the Gruinard and Beinn Airigh Charr basites). A similar association of metasediments with amphibolite sheets was described in the Gairloch area (Park 1964) and the Gairloch and Loch Maree sediments are generally regarded as stratigraphical equivalents (c.f. Park 1970).

Power and Park (1969) have shown that the amphibolite sheets associated with the metasediments (Aundrary and Kerrysdale sheets) are significantly different in their trace element content from the basic dykes (e.g. the South Sithean Mor basite). Like the metasediments the Beinn Airigh Charr and Gruinard basites have S5 fabric elements but show no evidence of "high grade" Badcallian fabrics or migmatisation. It can also be demonstrated that the Gruinard Bay basite is cut by the basic dykes (see Map 3A); these basites are therefore similar in age to the metasediments with which they are associated and may be basic sills older than the basic dykes, volcanic rocks contemporaneous with the metasediments, or para-amphibolites.

In view of the widespread distribution of these basite sheets and their intimate association with the metasedimentary rocks, it is considered that they most likely represent contemporaneous volcanic rocks or para-amphibolites. More detailed geochemical studies of these

basites may resolve these problems and prove a profitable line of future research.

D. DYKE RELATIONSHIPS AND CONDITIONS OF EMPLACEMENT IN THE GNEISS COMPLEX

Detailed dyke relationships were considered in Chapter VI.B,D where it was suggested that dyke emplacement was controlled by pre-existing structures, the S5 (Inverian) foliation playing a particularly important rôle in this respect.

In the Creag Mheall Beag area the First-Period dykes have a general W.N.W.-E.S.E. trend, but show local deflections and in one case branching (square 9786) concordantly to S5. The Second-Period dykes form thick sheets up to 100m. in width, and have numerous branches. In the south-west of the area however, where S5 is a closely-spaced foliation, the dihedral angle between branches is smaller than in the north-eastern part of the area where S5 is a less penetrative planar structure. The Third-Period dykes form thinner sheets and display greater variation in trend than either the First or Second-Period dykes. In the northern part of the area, branches of the Third-Period dykes are sometimes strongly discordant with S5 and individual branches display marked changes in trend (square 9787). Such features imply that dyke emplacement was controlled by fractures in the country rocks, rather than by magma pressure or by such comparatively regular planar structures as metamorphic foliation. In the southern part of the Creag Mheall Beag area, branches of Third-Period dykes show greater conformity with the regional trend of S5.

It was argued (see Ch.IV.D6) that the dykes were emplaced into hot country rocks towards the close of the M5 (Inverian) episode. The tendency for most of the dykes to form concordant sheets may be a

consequence of elevated country rock temperatures (Park and Cresswell, in press) where due to increased ductility, brittle fracturing of the country rock is inhibited with intrusion tending to follow foliation surfaces.

The tendency for the Third-Period dykes to exhibit more widespread discordance and for branches to be guided by fracture systems suggests that cooler country rock conditions prevailed in this part of the complex at the time of Third-Period dyke emplacement.

The igneous features in the Second-Period dykes of the Creag Mheall Beag area (see Ch.IV.B2) provide evidence concerning the pre-dyke attitude of S5 in this area; for it was suggested that the sub-horizontal layering developed in the Second-Period dykes is a gravitational layering of cumulus phases. Since the present attitude of this layering reflects only slight post-Lewisian rotation, and since most dykes form steeply inclined sheets, broadly concordant with S5, S5 in the Creag Mheall Beag area was thus imparted in its present steeply dipping attitude.

In the Kernsary area, dykes are few in number; the larger bodies mapped probably all form part of a single, branching but largely concordant sheet. In the northern part of the area this sheet is concordant with north-east-dipping S5, and the S6 foliation in the dyke is developed parallel to the dyke margins. Further south, S6 foliation in the dykes becomes more truly penetrative and there is general concordance of dyke margins, penetrative S6 foliation in the dykes, and modified S5 foliation in the gneisses. It is thus considered that the dykes were intruded parallel to S5, and that S6 was imparted parallel to it.

A few thin dykes, markedly discordant with S5, also outcrop in the Kernsary area; some of these have small offshoots, concordant with

S5. Most of these dykes are foliated parallel to their margins and, where the margins are markedly oblique to S5, S6 foliation in the dykes is thus markedly discordant with S5 in the gneisses. However, away from the dyke margins, S6 in the dykes gradually bends into parallelism with S5 in the gneisses.

The thin dykes of the Kernsary area may represent small feeder dykes between the larger concordant sheets (for example, the thin dykes which outcrop between the thick sheets of Meall na Maine and Meall Ghiuragarstidh are probably of this nature, although inadequate exposure and the effects of D8 deformation do not permit precise recognition of the field relationships). Alternatively, since the position of these thin dykes in the intrusion sequence is obscure, it is possible that they represent relatively late members of the dyke swarm (possibly equivalent to the Third-Period dykes of the Creag Mheall Beag area), intruded into country rocks which were brittle enough to fracture obliquely to the S5 foliation.

In the Beinn Airigh Charr area, Laxfordian deformation has imparted a penetrative foliation in the dykes and has considerably modified the pre-dyke structures. Detailed intrusion relationships are not easily discerned, but the situation seems to conform with that found in the southern part of the Kernsary area in which the first Laxfordian foliation in the dykes, dyke margins and S5 are all parallel.

The dykes of the Poolewe area form, for the most part, concordant sheets parallel to S5A. They occur both as thin, closely-spaced bodies and as much wider sheets with numerous branches, the former being more characteristic of the western side of the area, and the latter of the eastern side.

Locally dyke branching occurs parallel to adjacent S5A fold limbs (see Plate VI.1b); this can be demonstrated on both small and

large scales. Both branching frequency and dyke spacing is interpreted as a consequence of the structural control exerted by pre-existing foliation planes and not as the result of variation in Laxfordian deformation (see Ch.VI.B,D).

Thus the observations made in the three southern areas confirm the conclusions reached in the Creag Mheall Beag area that dyke emplacement occurred in a hot, but cooling Inverian complex, and in which the planar Inverian structures exerted considerable structural control over magma intrusion.

E. LARGE SCALE STRUCTURE

The areas mapped include portions of three large scale structures:-

- (i) The Carnmore Antiform
- (ii) The Letterewe Synform
- (iii) The Tollie Antiform

1. The Carnmore Antiform

This is a compound structure whose north-east limb and crestal area are defined by S5 (Inverian) foliation; on the south-west limb, steepening of dip is associated with S6 modifications (Laxfordian) of the Inverian fabrics. Throughout the antiform the basic dykes are broadly concordant with the dominant foliation of the gneisses; the dykes on the south-west limb of the structure are more thoroughly foliated than those on the north-east limb. These observations concerning the dykes, implying more intense Laxfordian deformation on the south-west limb of the antiform, are thus compatible with the more advanced development of Laxfordian fabrics recognised in the gneisses of that area.

The gentle plunge of the large F6 structures in the Beinn Airigh Charr area (see Ch.VI.E) suggests that the pre-F6 (i.e. S5)

foliation had a sub-horizontal attitude, whilst in the Poolewe area S5 also appears to have been initiated as a sub-horizontal structure. Thus a N.W.-S.E.-trending belt, several kilometres in width, of sub-horizontally disposed S5 occupied the southern portion of the Kernsary area and the Beinn Airigh Charr and Poolewe areas.

To the north-east of this belt, S5 dip increases progressively, whilst S5 becomes less penetrative, as evidenced by the better preservation of pre-S5 fabric elements.

It could be argued that the S5 foliation which forms the north-east limb and crestal area of the Carnmore antiform has been folded from an original, more uniform attitude into a large scale monoclinial structure. There are two alternative ways of explaining this structure:-

(i) If the steep north-east-dipping limb has been rotated into its present attitude from a less steeply inclined position, the D3 granulite facies gneisses which outcrop to the north of the Grunard river would have occupied structurally higher levels than the post-D3 metasediments. According to this hypothesis it is thus necessary to suggest that the high grade metamorphic rocks have been either folded or faulted into a position above the metasediments in D5 or pre-D5 events. Since there is no evidence in support of this hypothesis it is rejected.

(ii) Alternatively if S5 developed with steep dip and was subsequently rotated into a sub-horizontal attitude, the present outcrop represents at least a 7km. vertical section of the M5 metamorphic complex. For such a deep section the M5 metamorphic fabric variations are so small that this hypothesis is also rejected.

The favoured explanation of the large scale Inverian structure is that S5 developed with its present attitude (i.e. in those areas

which are not profoundly affected by Laxfordian deformation). Thus in the Creag Mheall Beag area S5 was imposed with a steeply dipping attitude, but with dips becoming progressively more flat-lying in the areas further south west. Comparable observations concerning original variation in Inverian foliation attitude were made in the Torridon area (Cresswell 1969). Ramsay (1963) has also described original regional variation in foliation attitude in association with Alpine nappe complexes, whilst Park (in press) considers much of the variation in Inverian foliation attitude to be original and developed in association with a nappe complex.

This interpretation of the Inverian structure implies that the dykes on the north-east limb and crestal area of the Carnmore antiform, attained their present attitude as a consequence of structurally controlled emplacement. The evidence corroborating this viewpoint was discussed in section VII.D.

2. The Letterewe Synform

The Beinn Airigh Charr area may be considered to form part of the Letterewe synformal tract in which the Gleann Tulacha metasediments are preserved at the present levels of exposure. This structure is essentially of early Laxfordian origin. In the gneisses, increasing south-westerly dips of the foliation are correlated with the progressive development of S6 fabrics. The basic dykes are generally concordant with the foliation in the gneisses; the more steeply inclined dyke sheets tend to be more schistose. Small scale F6 folds are not developed in either the gneisses or dykes.

The D6 (early Laxfordian) structure of the Beinn Airigh Charr area is therefore envisaged as a complex large scale shear zone (c.f. Ramsay & Graham, 1970, pp.809-811 and Fig.25). Sub-horizontally disposed S5 in the gneisses becomes progressively steepened and modified

into the S6 "shear" foliation. The two major crush zones depicted on Map 5A are considered to represent the location of two major D6 shear zones, now much modified by late stage deformation.

The basic dykes were probably intruded concordant or sub-concordant with the S5 foliation in the gneisses (see section VII.D) but were rotated into a more steeply inclined attitude in the D6 deformation, during which a "shear" foliation, the S6 fabric, was imparted as a modification of the original S5 fabric.

In the Gleann Tulacha metasediments and basite D6 is associated with gently plunging small scale and large scale folds. The gentle plunge of these folds attests to the formerly sub-horizontal attitude of the S5 foliation in this area, an observation also corroborated by the gently inclined attitude of S5, preserved on Creag Cairneasair. Thus the gneiss complex and its metasedimentary cover demonstrate contrasted styles of deformation in the phase of early Laxfordian crustal shortening.

The effects of D7 and D8 add complexity to, but do not fundamentally alter, the D6 major structure.

3. The Tollie Antiform

The gneisses in the Poolewe area form part of the north-east limb of the Tollie antiform. The geometry of this fold was discussed by Park (1969a). Structurally the Poolewe gneisses represent a continuation of the Craig Mhor Tollaidh block (Park, op.cit); the steeply-dipping foliation which forms the north-east limb of the Tollie antiform is defined by S5A although S6 and S7 have developed parallel to S5A. S5 is however a sub-horizontally disposed structure in the Poolewe area, and thus forms a continuation of the S5 "flat belt" which occurs to the north of Loch Maree.

The basic dykes in the Poolewe area show evidence of

structurally controlled emplacement, (see sections VI.B and VI.D); the dykes were thus intruded as steeply inclined sheets, sub-concordant with S5A. Laxfordian foliation in most of the Poolewe dykes was subsequently imparted parallel or sub-parallel to the S5A foliation in the gneisses.

4. The Loch Maree Fault

The outcrop of the Loch Maree fault has a N.W.-S.E. trend, the fault itself causing relative displacement of the south-west limb of the Letterewe synformal tract and the north-east limb of the Tollie antiform. The total displacement affecting Lewisian rocks cannot accurately be determined although post-Cambrian vertical displacement is known (Peach et al. 1907).

Analysis of S7 fabrics (see Ch.IV.C) showed that M7 effects in the Poolewe area are increasingly apparent in a south-easterly direction; a similar trend is also evident in the Beinn Airigh Charr area; however in the latter area M6 garnets in the dykes are fresh and show little evidence of D7 crushing and M7 replacement by epidote, features noted in the south eastern part of the Poolewe area. It is thus concluded that the rocks of the Beinn Airigh Charr area were originally even further north-west (8km.+) than any in the Poolewe area at the present level of exposure, or alternatively if the relative displacement is due to vertical movements, considerable downthrow to the north east is indicated.

F. GEOCHEMICAL ASSEMBLAGES AND A COMPARATIVE GEOCHEMICAL CHRONOLOGY

Holland and Lambert (in press) recognise four petrochemical assemblages in the Southern District of the Lewisian, three of which, the Gruinard, Kernsary and Gairloch assemblages, outcrop in the areas studied by the author.

They consider the Gruinard assemblage, which outcrops in the

Creag Mheall Beag area, to represent a primitive intermediate silica crust, depleted in Rb, U and Th, and fractionated under meta-plutonic conditions.

The Kernsary assemblage, members of which outcrop in the Kernsary and Beinn Airigh Charr areas, is considered to be a supra-crustal series deposited on the primitive crust, and first metamorphosed in the Inverian, while the Gairloch metasedimentary assemblages and associated basites (equivalents of the metasediments and basites near Loch Maree) are representatives of a younger supra-crustal series.

This interpretation based upon comparative geochemical methods thus represents considerable divergence from the chronology proposed in this thesis. Three points however are made in defence of the author's viewpoint.

(i) The structural sequence proposed for the Kernsary area is at least as long as that in the Creag Mheall Beag area, and it is not possible on the basis of structural analysis to demonstrate the existence of basement-cover relationships between the gneisses in the Creag Mheall Beag and Kernsary areas.

(ii) If, as suggested in this thesis, the Gruinard and Gleann Tulacha metasediments are stratigraphically equivalent, the basite sheets associated with these metasediments are pre-dyke in age and cannot, therefore, be the supra-crustal representatives of the Scourie dyke swarm.

(iii) The geochemical difference between the Gruinard and Kernsary assemblages may be explained by regional variation in the grade of Badcallian metamorphism; for example in one possible model, the gneisses which constitute the Gruinard assemblage are subjected to prolonged Badcallian granulite facies metamorphism whilst the Kernsary assemblage experienced Badcallian metamorphism in amphibolite facies and may have thus concentrated such volatile elements as K, Rb, Th and U,

which migrated out of the Gruinard assemblages.

In addition, the effects of the Laxfordian K-metasomatic event which affected the Kernsary assemblage may account for some of the observed chemical contrasts.

G. THE EXTENT OF THE LAXFORDIAN COMPLEX

All of the areas studied have experienced Laxfordian deformation and metamorphism. In the Creag Mheall Beag area the Laxfordian effects are slight, enabling a clear distinction to be made between Laxfordian and Inverian phenomena and permitting more detailed study of Inverian and Badcallian events. Thus, whilst none of the dykes preserves its original igneous fabric, some dykes contain original igneous plagioclase and have relict ophitic texture; penetrative foliation is confined to thin dykes and to the margins of the wider dykes. Most of the fabrics and structures in the gneisses of the Creag Mheall Beag area record their Scourian provenance.

In the areas further south, relict igneous textures and fabrics in the dykes are less common and even the widest dykes tend to be foliated throughout. In the gneisses of these areas the Badcallian and Inverian fabrics are recognisable only in extremely modified forms and Laxfordian fabrics predominate.

Thus, since all the dykes studied show some evidence of Laxfordian deformation and metamorphism, all of the areas studied may in this sense be considered part of the Laxfordian complex. However Laxfordian effects upon the gneiss fabrics only become strictly penetrative in the Kernsary area and further south. Exact delimitation of the northern margin of the Laxfordian complex is impossible since the criteria upon which it is based are progressive in their development; thus a zone rather than a line is a more realistic boundary between Laxfordian and pre-Laxfordian complexes. The orostal area of the

Carnmore antiform may be regarded as such a zone for the following reasons:-

(i) The cretal area represents situations where the S5 foliation forming the north-east limb of the Carnmore antiform begins to dip south-eastwards on the south-west limb of this structure and the adjacent north-west limb of the Letterewe synform. The cretal area thus divides the Letterewe synform (a large-scale Laxfordian structure) from the north-east limb of the Carnmore antiform (a large-scale Inverian structure). Thus, to the north of the cretal area of the Carnmore antiform, there are no large-scale Laxfordian structures in the region described here.

(ii) North of this cretal area, and in marked contrast with areas further south, S6 is not a well developed planar structure in the gneisses, nor is it always penetrative of the wider dyke bodies.

(iii) The effects of post-D6 events are only occasionally registered in the complex to the north of this zone, whereas further south both D7 and D8 are associated with large-scale folding and metamorphic fabric development.

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